

VIRTUAL FUEL CELL SYSTEM

Rachel Jennifer Taylor

A thesis submitted for the degree of
Engineering Doctorate

© Newcastle University December 2014
School of Electrical, Electronic and Computer Engineering

Abstract

The purpose of this project was to build a computer model able of running virtual simulations and emulations of fuel cell (FC) systems. This was aimed at the transport market and modern built environment. The project incorporates the novel use of hardware, firmware and software operating in real-time to simulate real applications in vehicles and buildings.

A fuel cell system is a complex assembly of components, all of which are all critical to its performance. To get the best from the system each of the system components must be optimized. Current practice uses prototyping of real hardware and testing. Such work is specific to single FC suppliers and is based on off-line modeling or real-time analysis against monitored loads.

The innovation in this project is in integrating the optimization step into the development of the complete system. The technical breakthrough is shown through closing the development gap between concept and final design by creating a real-time simulation and emulation process to develop optimum FC systems for the transport and built environment markets. The virtual fuel cell can be operated safely outside the limits that it would normally encounter for given criteria. This extends the know-how beyond conventional testing. The time consuming and costly setting up of hardware tests with an actual fuel cell is therefore not required.

This project outcome gives the new ability to design and engineer optimized FC systems without the risk of component / subsystem redundancy. It relinquishes the requirement for a hydrogen source, cooling; pumps, water etc. and gives rise to a completely safe test environment.

This thesis is dedicated to my mum Hilary, dad Jim and brother Bobby who supported me through every step of my research. Without their support I would not be where I am today.

I would also like to dedicate this to the late John Holden and his family. John encouraged me throughout my research and saw the potential in this project from the beginning.

Acknowledgements

I would like to begin by expressing my appreciation to those who funded and supported this research project: The Engineering and Physical Sciences Research Council, HILTech Developments and The Engineering Doctorate scheme at Newcastle University.

Thanks are given to my academic supervisors; Volker Pickert and Matthew Armstrong who offered advice, guidance and support throughout my years at Newcastle.

I would also like to thank my industrial supervisor John Holden, who sadly passed away during my research. It was John who saw the potential in a Virtual Fuel Cell System and encouraged me to embark on this project.

Finally I would like to thank CPI for allowing me to use their fuel cell rig in order to validate the results of my model.

Table of Contents

CHAPTER 1. INTRODUCTION	1
1.1 THESIS OVERVIEW	1
1.2 UNIQUE ASPECTS OF THE WORK.....	2
1.3 PUBLISHED WORK	4
CHAPTER 2. INTRODUCTION TO FUEL CELLS AND THEIR APPLICATIONS	5
2.1 INTRODUCTION	5
2.2 AUTOMOTIVE CONSIDERATION	6
2.2.1 PEMFC Simulation and Control for vehicles	7
2.2.2 Commercial and Industrial	10
2.3 FUELLING A FUEL CELL	11
2.3.1 Hydrogen Production from Natural Gas	13
2.3.2 Hydrogen Production from Coal Gas.....	14
2.4 HYDROGEN PRODUCTION FROM BIO FUELS.....	15
2.5 HYDROGEN PRODUCTION FOR AUTOMOTIVE APPLICATIONS.....	15
2.6 FUEL STORAGE	15
2.6.1 Compressed Gas	15
2.6.2 Cryogenic Liquid	16
2.6.3 Other options for hydrogen storage	17
2.7 BARRIERS TO MARKET	17
2.7.1 Cost Reductions	17
2.7.2 Reliability.....	18
2.7.3 System Integration	19
2.7.4 Safety.....	19
2.7.5 Infrastructure	20
CHAPTER 3. FUEL CELL SYSTEMS	22
3.1 INTRODUCTION	22
3.2 ACID ELECTROLYTE FUEL CELL	23
3.3 ALKALINE ELECTROLYTE FUEL CELL	24
3.4 LIMITATIONS ON CURRENT PRODUCTION.....	25
3.5 THE BASIC CONSTRUCTION OF A FUEL CELL.....	26

3.5.1	<i>The Bipolar Plate</i>	26
3.5.2	<i>Gas Supply and Cooling</i>	27
3.5.3	<i>Internal manifolding</i>	28
3.6	EFFICIENCY OF A FUEL CELL	29
3.7	CAUSES FOR VOLTAGE LOSS	32
3.7.1	<i>Activation Losses</i>	35
3.7.2	<i>Fuel Crossover/Internal Current Losses</i>	37
3.7.3	<i>Ohmic Losses</i>	37
3.7.4	<i>Mass Transport/Concentration Losses</i>	38
3.7.5	<i>Total Fuel Cell Losses</i>	38
CHAPTER 4.	THE BALANCE OF PLANT (BOP)	40
4.1	OVERVIEW	40
4.2	AIR SUPPLY SYSTEM	41
4.3	HYDROGEN SUPPLY SYSTEM	42
4.4	COOLING SYSTEM	43
4.5	DC-DC CONVERTER	43
CHAPTER 5.	TYPES OF FUEL CELL	45
5.1	INTRODUCTION	45
5.2	PROTON EXCHANGE MEMBRANE FUEL CELL (PEMFC)	45
5.3	DIRECT METHANOL FUEL CELLS (DMFC)	50
5.4	ALKALINE FUEL CELL	53
5.5	PHOSPHORIC ACID FUEL CELL (PAFC)	55
5.6	SOLID OXIDE FUEL CELL (SOFC)	57
5.7	MOLTEN CARBONATE FUEL CELL (MCFC)	59
CHAPTER 6.	FUEL CELL MODELING	61
6.1	INTRODUCTION	61
6.2	MODEL PARAMETERS AND SELECTION	62
6.2.1	<i>Theoretical</i>	64
6.2.2	<i>The state of the model</i>	64
6.2.3	<i>System boundary</i>	65
6.2.4	<i>Spatial dimension</i>	65
6.2.5	<i>Complexity</i>	66
6.2.6	<i>Source code</i>	66

6.2.7	<i>Validation</i>	66
6.3	THEORETICAL FUEL CELL MODELS CONSTRUCTED FROM LITERATURE	67
6.4	COMMERCIAL FUEL CELL MODELS	67
6.5	REAL – TIME SIMULATION	68
CHAPTER 7.	SHORTLISTED MODELS.....	71
7.1	INTRODUCTION	71
7.2	MATLAB SIMULINK MODEL	71
7.2.1	<i>Overview</i>	71
7.2.2	<i>Mathworks – Simplified Model</i>	71
7.2.3	<i>Mathworks – Detailed model</i>	72
7.2.4	<i>Conclusion</i>	73
7.3	COLEEN SPIEGEL MODEL.....	73
7.3.1	<i>Overview</i>	73
7.3.2	<i>Conclusion</i>	74
7.4	NEHRIR.....	74
7.4.1	<i>Overview</i>	74
7.4.2	<i>Conclusion</i>	77
CHAPTER 8.	AUXILIARY SYSTEM MODELING.....	78
8.1	INTRODUCTION	78
8.2	AIR SUPPLY SYSTEM	80
8.2.1	<i>The Compressor</i>	80
8.2.2	<i>The Manifold</i>	81
8.2.3	<i>Supply Manifold</i>	82
8.2.4	<i>Return Manifold</i>	83
8.2.5	<i>Humidifier</i>	84
8.3	HYDROGEN SUPPLY SYSTEM	84
8.4	COOLING SYSTEM.....	84
CHAPTER 9.	DC-DC CONVERTER	85
9.1	INTRODUCTION	85
9.2	BUCK CONVERTER.....	86
9.3	BOOST CONVERTER.....	88
9.4	BUCK-BOOST CONVERTER	90
9.5	FURTHER DEVELOPMENT OPPORTUNITIES	92

CHAPTER 10. BUILDING THE FUEL CELL SYSTEM	93
10.1 INTRODUCTION	93
10.2 COMBINING THE FUEL CELL AND AUXILIARY MODELS.....	93
10.3 RUNNING THE MODEL ON DSPACE.....	95
10.4 REAL-TIME INTERFACE (RTI)	96
10.5 CONTROL DESK USER INTERFACE	97
10.6 OUTPUTS OF THE VFCS	98
10.7 EMULATORS CURRENTLY ON THE MARKET	99
CHAPTER 11. MODEL VALIDATIONS	103
11.1 THE BALLARD NEXA	103
11.2 VALIDATION SET UP	105
11.3 INITIAL COMPARISONS BETWEEN THE VFCS AND BALLARD NEXA	107
11.4 INCLUSION OF THE TEMPERATURE OUTPUT FROM THE BALLARD INTO THE VFCS.....	107
11.5 VARIATION OF THE NUMBER OF CELLS WITHIN THE STACK.....	108
11.6 REVIEWING THE VOLTAGE LOSS COMPONENTS WITH THE MODEL	109
11.6.1 Activation Losses	110
11.6.2 Concentration Losses.....	111
11.7 TEST CONDITIONS	113
11.8 COMPARISON OF LOAD PROFILES.....	114
CHAPTER 12. CONCLUSIONS	119
12.1 SATISFYING PROJECT OBJECTIVES	119
12.2 RECOMMENDATIONS FOR FUTURE WORK.....	121
CHAPTER 13. APPENDICES	123
CHAPTER 14. REFERENCES	184

List of Figures

FIGURE 1-1 VIRTUAL FUEL CELL SYSTEM EMULATOR CONSTRUCTION.....	1
FIGURE 2-1 TOYOTA HIGHLANDER FCHV CONCEPT AT 2008 NYIAS	6
FIGURE 2-2 FUEL CELL CAR.....	7
FIGURE 2-3 POWER DENSITY AND CURRENT DENSITY IN A FUEL CELL.....	9
FIGURE 2-4 AUTOMOTIVE FUEL CELL SYSTEM.....	9
FIGURE 2-5 CHP SYSTEM WITH A SOLID OXIDE FUEL CELL	11
FIGURE 2-6 METHODS OF HYDROGEN PRODUCTION.....	12
FIGURE 2-7 STEAM REFORMING PROCESS	13
FIGURE 2-8 TOYOTA FCHV BUS (EXPO 2005 AICHI JAPAN SPECIFICATION)	16
FIGURE 2-9 (1) 3 SECONDS AFTER IGNITION (2) 1 MINUTE AFTER IGNITION AND (3) 1.5 MINUTES AFTER IGNITION.	20
FIGURE 2-10 PETROLEUM USE BY VEHICLES IN THE USA	21
FIGURE 3-1 WILLIAM GROVE EXPERIMENT	22
FIGURE 3-2 CURRENT FLOW IN AN ACID ELECTROLYTE FUEL CELL.....	23
FIGURE 3-3 CURRENT FLOW IN AN ALKALINE ELECTROLYTE FUEL CELL.....	24
FIGURE 3-4 ENERGY DIAGRAM FOR A SIMPLE EXOTHERMIC CHEMICAL REACTION	25
FIGURE 3-5 TWO BIPOLAR PLATES SHOWING BOTH SIDES.	26
FIGURE 3-6 FUEL CELL STACK.....	27
FIGURE 3-7 EXTERNAL MANIFOLDS FITTED TO THE FUEL CELL STACK.	28
FIGURE 3-8 BASIC FUEL CELL INPUTS AND OUTPUTS.....	29
FIGURE 3-9 VOLTAGE LOSSES WITHIN THE FUEL CELL.....	32
FIGURE 3-10 ACTIVATION LOSSES WITHIN A FUEL CELL	33
FIGURE 3-11 OHMIC LOSSES WITHIN A FUEL CELL.....	34
FIGURE 3-12 CONCENTRATION LOSSES WITHIN A FUEL CELL.....	34
FIGURE 3-13 TAFEL EQUATION	36
FIGURE 3-14 OPERATIONAL FUEL CELL PLOT FOR VOLTAGE VS. CURRENT DENSITY.....	39
FIGURE 4-1 FUEL CELL SYSTEM AND ITS AUXILIARIES.....	40
FIGURE 4-2 AIR SUPPLY SYSTEM	42
FIGURE 4-3 HYDROGEN SUPPLY SYSTEM	42
FIGURE 4-4 COOLING SYSTEM	43
FIGURE 4-5 DC-DC CONVERTER.....	44
FIGURE 5-1 TYPES OF FUEL CELL	45
FIGURE 5-2 STRUCTURE AND FLOW OF A PEMFC	47
FIGURE 5-3 TEMPERATURE DEPENDENCE OF THE CELL	49
FIGURE 5-4 POTENTIAL USES FOR DMFCs	51
FIGURE 5-5 STRUCTURE AND FLOW OF A DIRECT METHANOL FUEL.....	52
FIGURE 5-6 STRUCTURE OF AN ALKALINE FUEL CELL	53
FIGURE 5-7 STRUCTURE OF A PHOSPHORIC ACID FUEL CELL	56

FIGURE 5-8 STRUCTURE OF A SOLID OXIDE FUEL CELL	58
FIGURE 5-9 STRUCTURE OF A MOLTEN CARBONATE FUEL CELL	59
FIGURE 6-1 FUEL CELL SYSTEM.....	65
FIGURE 6-2 OFFLINE SIMULATION (A) AND (B) ALONGSIDE REAL-TIME SIMULATION (c)	69
FIGURE 6-3 REAL-TIME SIMULATION PROCESS STEPS	70
FIGURE 6-4 SIMULATION TIME-STEP BY APPLICATION	70
FIGURE 7-1 THE SIMULINK FC BLOCK AND SIMPLIFIED TAFEL SLOPE	72
FIGURE 7-2 MATHWORKS DETAILED FC MODEL	72
FIGURE 7-3 VOLTAGE AND VOLTAGE LOSS CALCULATION WITHIN THE NEHRIR SIMULINK MODEL FOR PEMFCs	76
FIGURE 8-1 FUEL CELL SYSTEM.....	79
FIGURE 8-2 COMPRESSOR MODEL INPUTS AND OUTPUTS	80
FIGURE 8-3 LUMPED MANIFOLD MODEL INPUTS AND OUTPUTS	82
FIGURE 8-4 SUPPLY MANIFOLD MODEL INPUTS AND OUTPUTS.....	82
FIGURE 8-5 SUPPLY MANIFOLD MODEL INPUTS AND OUTPUTS.....	83
FIGURE 9-1 DC-DC CONVERTER.....	85
FIGURE 9-2 CIRCUIT DIAGRAM SHOWING A BUCK CONVERTER.....	86
FIGURE 9-3 SIMULINK BLOCK DIAGRAM SHOWING USE OF A BUCK CONVERTER WITH THE MATLAB SIMULINK FUEL CELL BLOCK.....	87
FIGURE 9-4 CIRCUIT DIAGRAM SHOWING A BOOST CONVERTER	88
FIGURE 9-5 SIMULINK BLOCK DIAGRAM SHOWING USE OF A BOOST CONVERTER WITH THE MATLAB SIMULINK FUEL CELL BLOCK.....	89
FIGURE 9-6 CIRCUIT DIAGRAM SHOWING A BUCK-BOOST CONVERTER.....	90
FIGURE 9-7 SIMULINK BLOCK DIAGRAM SHOWING USE OF A BUCK-BOOST CONVERTER WITH THE MATLAB SIMULINK FUEL CELL BLOCK.....	91
FIGURE 10-1 VFCS BUILD AND VALIDATION PLAN	93
FIGURE 10-2 COMPLETED VFCS.....	94
FIGURE 10-3 dSPACE PROCESSOR AND PC SET UP	96
FIGURE 10-4 dSPACE USER INTERFACE	97
FIGURE 10-5 INITIAL READINGS FROM THE VFCS	98
FIGURE 10-6 INITIAL OUTPUT CORRECTED FOR I _{LIM}	99
FIGURE 10-7 INITIAL VOLTAGE OUTPUT PLOT.....	99
FIGURE 10-8 HIL SIMULATION OF A FUEL CELL.....	100
FIGURE 10-9 MAGNUM HIL SET UP FOR FUEL CELLS	100
FIGURE 10-10 VERIFICATION OF THE MAGNUM MODEL UNDER BOTH A) STATIONARY AND B) DYNAMIC LOADING	101
FIGURE 11-1 BALLARD NEXA 1.2kW PEMFC	103
FIGURE 11-2 BALLARD FUEL CELL SCHEMATIC.....	104
FIGURE 11-3 THE LOAD INPUT INTO THE BALLARD AND HILTECH TEST BED	105
FIGURE 11-4 THE ACTUAL LOAD ON THE BALLARD FUEL CELL	106
FIGURE 11-5 INITIAL ERRORS IDENTIFIED WITHIN THE MODEL	107
FIGURE 11-6 AVERAGED TEMPERATURE READINGS FROM THE BALLARD NEXA.	108

FIGURE 11-7 EFFECTS OF INCREASING THE NUMBER OF CELLS	109
FIGURE 11-8 RUNNING THE MODEL WITHOUT VOLTAGE LOSSES	110
FIGURE 11-9 VOLTAGE PLOT WITH ACTIVATION LOSSES.	110
FIGURE 11-10 VOLTAGE PLOT WITH CONCENTRATION LOSSES.....	112
FIGURE 11-11 FINALISED MODEL OUTPUT	113

List of Tables

TABLE 2-1 EXAMPLES OF FUEL CELL APPLICATIONS	5
TABLE 2-2 COMPARISON OF FUEL PRODUCTION COSTS	12
TABLE 2-3 PROPERTIES OF HYDROGEN RICH FUELS.....	13
TABLE 2-4 WARM START FUEL ECONOMIES AND USAGE FOR VARIOUS AIR CONTROL CASES	18
TABLE 2-5 COMPARISON OF THE ENERGY STORED IN HYDROGEN AND GASOLINE	20
TABLE 3-1 GIBBS FREE ENERGY OF WATER	29
TABLE 3-2 COMMON I0 VALUES FOR SELECTED METALS.....	36
TABLE 5-1 PEMFC SUMMARY TABLE	45
TABLE 5-2 DMFC SUMMARY TABLE	50
TABLE 5-3 ALKALINE FUEL CELL SUMMARY TABLE	53
TABLE 5-4 PHOSPHORIC ACID FUEL CELL SUMMARY TABLE.....	55
TABLE 5-5 SOLID OXIDE FUEL CELL SUMMARY TABLE	57
TABLE 5-6 MOLTEN CARBONATE FUEL CELL SUMMARY TABLE.....	59
TABLE 7-1 SPIEGEL KEY PARAMETERS[80].....	73
TABLE 8-1 TIME CONSTANTS FOR AND AUTOMOTIVE PEMFC.....	78
TABLE 10-1 SIMULINK SOLVERS.....	96
TABLE 11-1 BALLARD FUEL CELL PARAMETERS	104
TABLE 11-2 HILTECH TEST BED OUTPUTS	106

List of Symbols

A	fuel cell active area
α	the charge transfer coefficient
ϵ_{fc}	exegetic efficiency
E	fuel cell voltage
E^0	EMF at standard pressure
F	Faraday constant
Δg_f	Gibbs free energy
γ	ratio of specific heat
Δh_f	enthalpy of formation (calorific value)
I	fuel cell current
i	current density
i_l	limiting current density
i_n	internal current losses
i_o	exchange current
LHV	fuel lower heating value
λ	stoichiometric ratio
m_{fc}	mass flow rate
m_w	mass of water
m_a	mass of the dry air
N	Avogadro's number
η_c	efficiency of the compressor
η_m	efficiency of the motor
ω	humidity ratio
θ	relative humidity
P	pressure of the system
P_w	partial pressure of the water
P_{sat}	saturated vapor pressure
R	ideal gas constant
Re	Reynolds number,
R	area specific resistance
T	temperature
W_{fc}	fuel cell power

Chapter 1. Introduction

1.1 Thesis Overview

In this thesis the use of fuel cells and their role in a sustainable future are explained. Fuel cells are not a new technology however they have yet to be fully utilized in the mass market. The types of fuel cell available are discussed alongside the merits of each. Fuel cells need a range of auxiliary components to function; these are also identified and explored.

There has been much work carried out on fuel cell modeling and steps have been taken in producing a virtual fuel cell system, such as the one proposed for this thesis. Current research is reviewed with a focus on the inclusion of auxiliaries and running the model in real-time. The ability to model and run a fuel cell simulator in real-time will greatly aid in the research and development of fuel cell vehicles and other applications.

The emulator discussed in this thesis consists of a validated model; including both a PEM (proton exchange membrane) fuel cell stack alongside its auxiliary components. Additionally the emulator is to include a DC-DC converter to step up the voltage and provide the output power. The DC-DC converter is discussed but future work is required to develop this into a marketable product. The emulator will be constructed as shown in Figure 1-1.

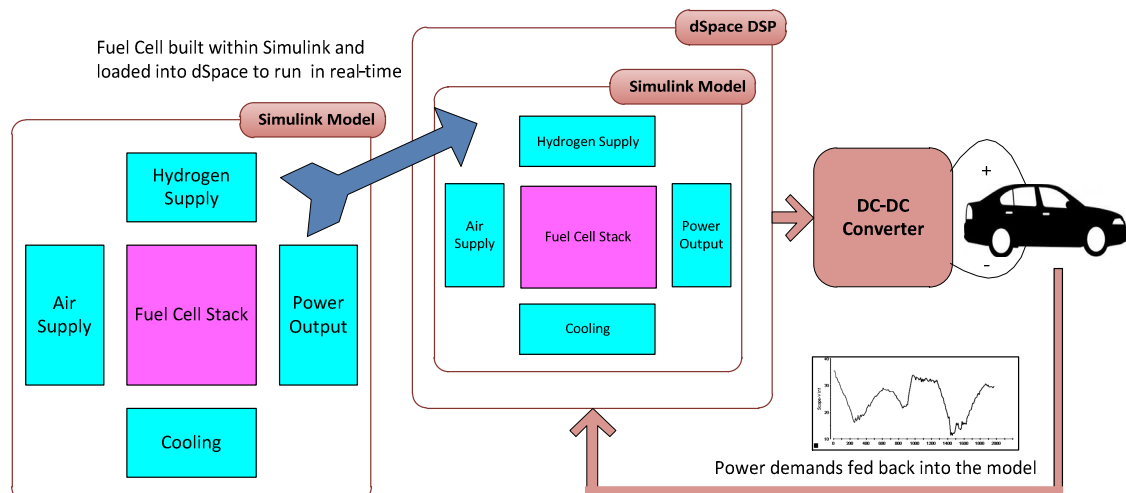


Figure 1-1 Virtual Fuel Cell System Emulator Construction

The real-time emulator removes the need for a fuel cell in the early development stages and allows a variety of fuel cell options to be explored before the user need commit to purchasing a fuel cell unit.

The thesis structure is as follows;

- Chapter's two to five give an overview of fuel cells, their applications, the different types available and the auxiliaries required to run the fuel cell effectively.
- Chapters six and seven review current research on fuel cell modeling, the key parameters to consider and investigates the benefits of three shortlisted examples.
- Chapter eight reviews modeling the auxiliary components within the fuel cell system.
- Chapter nine discusses the use of a DC-DC converter for later inclusion in the emulator.
- Chapter ten looks at construction the virtual fuel cell system by integrating models for the fuel cell itself alongside the auxiliary components.
- Chapter eleven shows the process used to validate the model output alongside the outputs of a physical fuel cell.
- Chapter twelve provide an overall set of conclusions and recommendations for further work.

1.2 Unique Aspects of the Work

When embarking on this research it was felt that idea of creating a virtual fuel cell system to run in real-time was in itself novel and had not yet been

investigated with the intent of bringing this technology to market. Once the project was underway however, it was discovered that there was already a real-time fuel cell emulator available, produced by Magnum Automatisierungstechnik GmbH, Germany. On investigation of this model it was clear that, although the initial concept was the same, Magnum did not publically share any detail on the governing equations applied within the subsystems of their model. [1] This meant the virtual fuel cell system could not be built on available technology and remained novel in its output.

The novelty of this project therefore lies in the combination of proven fuel cell models to create a cost effective and accurate fuel cell system. The level of detail is controlled as such to keep the processing time to a minimum and negate the requirement for a more powerful processor, allowing the fuel cell to run in real-time.

The virtual fuel cell system builds on current proven research and combines the fuel cell model with auxiliaries to produce a complete system.

The objectives applied in order to meet these statements were as follows

- Investigate current fuel cell models to establish which would be most suitable for use in real-time simulation.
- Investigate how these models could be modified for more effective application in real-time simulation.
- Produce a complete model of a fuel cell system which requires minimal processing power.
- Validate the virtual fuel cell system against a physical fuel cell to ensure the assumptions made in order to reduce processing power do not have negative effects on the output of the model.

1.3 Published Work

The following peer reviewed publications and conference proceedings have stemmed from this research

- August 2011. EPE 2011. Birmingham UK
Selection of a Semi-Empirical Model for use as a Real-time Model in a Virtual Fuel Cell
R. Taylor, V. Pickert
- July 2011. 4th International Conference on Experiments, Process System Modeling, Simulation and Optimization. Athens, Greece.
Evaluating the Accuracy and Suitability of Available PEM Fuel Cell Models for use in a Virtual Fuel Cell System
R. Taylor, V. Pickert, M. Armstrong, J. Holden
- January 2011. Newcastle University EECE Conference. Newcastle, UK
Evaluating the Suitability of Available Proton Exchange Membrane (PEM) Fuel Cell Models for use in a Virtual Fuel Cell system
R. Taylor, V. Pickert, M. Armstrong
- January 2010, Newcastle University EECE Conference, Newcastle, UK
Virtual Fuel Cell System: Project Overview
R. Taylor, V. Pickert, M. Armstrong

Chapter 2. Introduction to Fuel Cells and their Applications

2.1 Introduction

A fuel cell produces electricity by utilizing the chemical energy stored within a fuel. This is achieved through a chemical reaction with oxygen or another oxidizing agent. The most common fuel is hydrogen but other fuel can be used for example hydrocarbons, such as natural gas, and alcohols, such as methanol. [2-4]. Fuel cells are dissimilar from batteries as they require a continuous source of fuel and oxygen to sustain the chemical reaction. However, as long as these inputs are continuously supplied they can produce electricity constantly [5].

Fuel cell applications can vary as they produce power anywhere between 1W to 10MW. A fuel cell can be applied to almost any application that requires power. The development of fuel cells in each of these ranges will have an immediate impact in the correlated technology listed in Table 2-1.

1 W – 1 kW	Mobile phones, laptops and other personal electronic equipment.
1kW - 100kW	Domestic, military and public transportation.
1MW - 10MW	Distributed power (grid quality AC)

Table 2-1 Examples of fuel cell applications

One area in particular in which the fuel cell will have a substantial impact in the future will be domestic and public transportation. The fuel cell will reduce the design complexity of a vehicle and is therefore well adapted to this application.



Figure 2-1 Toyota Highlander FCHV concept at 2008 NYIAS¹

The major motor manufacturers are increasingly investing in incorporating fuel cells into their future designs (see Figure 2-1). The reliance of today's cars on mechanical systems would be removed by development of a 'drive-by-wire' vehicle. An entirely electronic vehicle would considerably reduce the number of moving parts required in a car and therefore lessen the likelihood of failure [6]. For lower power applications the fuel cell has great benefits over batteries as they do not need to be recharged, only re-fuelled. Additionally, they have much higher power densities than current batteries on the market. This means the physical size of the cell can be reduced while applying the same power, significantly saving space [7].

2.2 Automotive consideration

Fuel cells in automotive applications have a number of constraints that must be considered. This includes restrictions on available space in the vehicle and fast power response and start up times [8]. Fuel cells entail a number of auxiliaries which must be incorporated into the vehicle and size and positioning of these within the vehicle must be considered (see Figure 2-2).

Polymer electrolyte membrane fuel cells (PEMFCs) are the most extensively tested and used fuel cell for non-hybrid vehicle propulsion. Their fast start-up and response times makes them favorable in automotive application, although as with any fuel cell, there are difficulties in implementing them. Direct methanol

¹ Photo from <http://autocarmodifications.blogspot.co.uk/2013/03/toyota-supports-realizing-hydrogen.html>

fuel cells are another viable option for automotive applications but must be developed further to achieve higher power densities and more stable operation [9, 10].

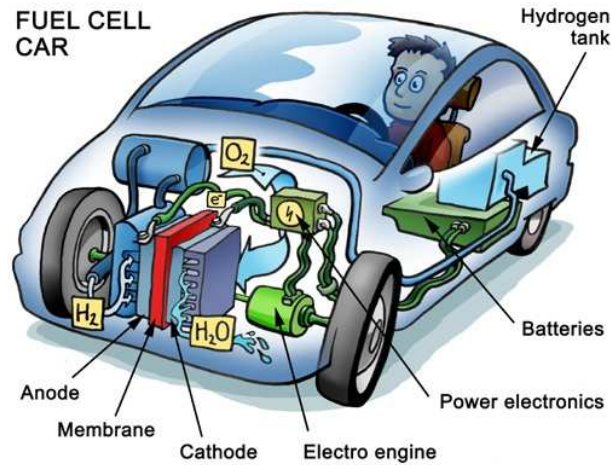


Figure 2-2 Fuel Cell Car²

The fuel supply also needs to be considered. The liquid form of hydrogen has a very high energy density, yet it is expensive to produce and difficult to obtain. Storing hydrogen fuel can be problematic due to its high combustibility and hydrogen embrittlement. This is when hydrogen impregnates the metal reducing the ductility and increasing the risk of brittle fracture.

2.2.1 PEMFC Simulation and Control for vehicles

Vehicle simulations are an important analysis tool for improving and optimizing vehicle systems. The efficiency of the fuel cell is determined within these simulations by using the fuel cells governing equations. The PEM fuel cell performance can be determined if the voltage, current and power are known to give the exoegetic efficiency [11]:

$$\epsilon_{fc} = \frac{\dot{W}_{fc}}{\dot{m}_{fc} \times \text{LHV}}$$

equation 2-1

Where \dot{W}_{fc} is the fuel cell power produced given in kW, \dot{m}_{fc} is the mass flow rate of fuel expended in the fuel cell reaction, given in kg/s and LHV is the fuel lower heating value given in kJ/kg. The second law of thermodynamics (entropy of an

² Photo from http://en.wikipedia.org/wiki/Hydrogen_vehicle

isolated system never decreases) is taken into account when calculating the exoegetic efficiency of the process. The fuel cell power produced, W_{fc} , can be calculated from the voltage and current:

$$W_{fc} = \frac{E \times I}{1000}$$

equation 2-2

Where E is the fuel cell voltage in volts and I is the fuel cell current in amps.

Simulation tools have the ability to model voltage-current density relationships. They also analyze the effects of cathode pressure and operating temperature on fuel cell voltage, power density, and exoegetic efficiency. For a given current density, increasing cathode pressure or increasing fuel cell operating temperature generally results in higher voltage, higher power density, and higher exoegetic efficiency [12]. Simulators can easily upsize the fuel cell and determine the effects of scale based on the current density.

$$I = i \times A$$

equation 2-3

Where i is the current density in A/cm² and A is the fuel cell active area in cm².

Substituting this back into equation 2-1 allows any size fuel cell to be modeled by specifying the fuel cell active area.

$$\epsilon_{fc} = \left(\frac{\frac{E \times i}{1000}}{(m_{fc}/A) \times LHV} \right)$$

equation 2-4

The relationship between power density and current density in a fuel cell is demonstrated below in Figure 2-3.

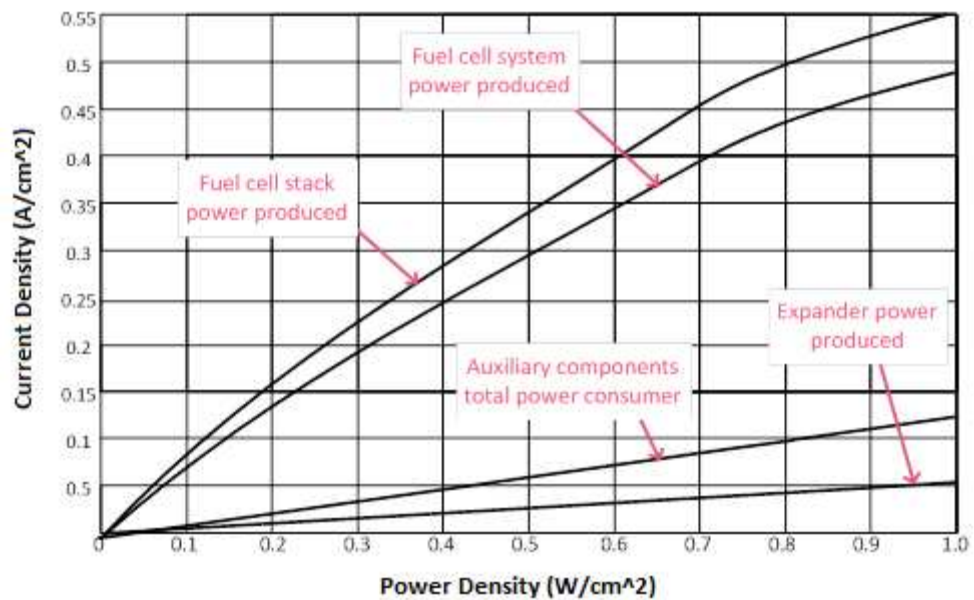


Figure 2-3 Power Density and Current Density in a Fuel Cell

This shows that increasing the current density of the fuel cell, while increasing the power output does not draw significantly from the auxiliaries. Therefore increasing the current density will in turn increase the efficiency of the fuel cell [13].

Fuel cells also need auxiliary components to support the operation of the fuel cell stack and as such these must be taken into account when analyzing the performance of the system. An example of a fuel cell system designed for use in an automobile is shown below in Figure 2-4.

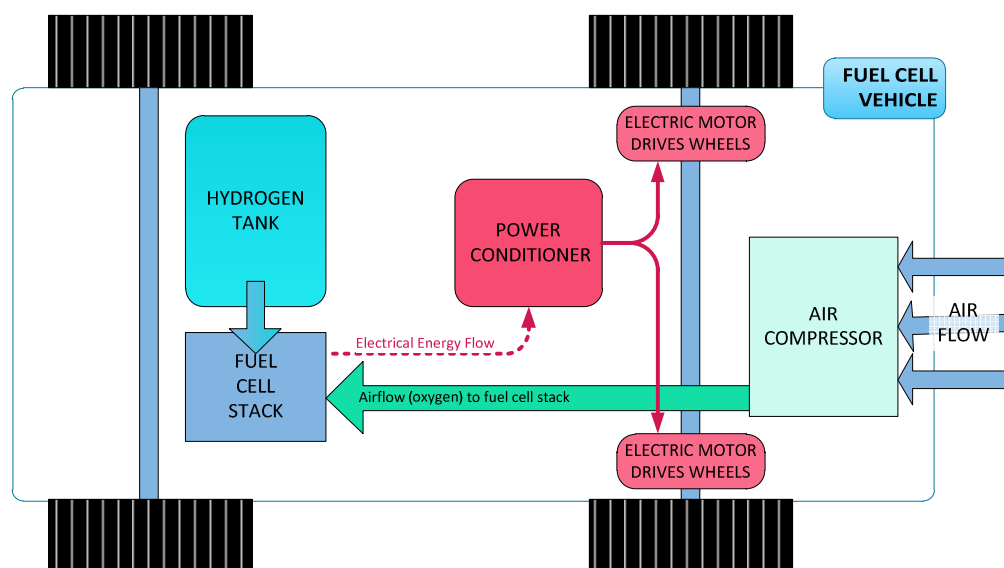


Figure 2-4 Automotive Fuel Cell System

The auxiliary units shown in Figure 2-4 are: air compressor to feed the right amount of air into the fuel cell stack, hydrogen tank to supply hydrogen to the stack (both the hydrogen and air supply will need to be humidified before entering the stack however this is not shown on the diagram), power conditioner to regulate the power supply before powering the electric motors which drive the wheels of the vehicles. Each of these components influences the FC performance and is needed to successfully model the fuel cell system and determine the total efficiency. Governing equations representing each of these auxiliary components are used to predict the ability of a fuel cell system to meet a desired vehicle driving cycle, estimate fuel economy, and implement a supervisory control strategy.

2.2.2 Commercial and Industrial

One of the more established applications for fuel cells is stationary power. These fuel cell units are applied in a number of applications. Supplementary power for the power grid means it is possible to activate the fuel cell during peak times, reducing total energy costs. Using fuel cells as backup power is a very efficient form of reliable backup [9]. It is estimated that over a thousand of the smaller stationary fuel cells (<10 kilowatts) have been manufactured to power homes and provide backup power [14]. In isolated locations fuel cells are an ideal form of power as they are reasonably small in size and fuel can be transported to where it is needed. Similarly fuel cells can be used as stand-alone power plants for towns and cities or distributed generation for buildings [15].

Polymer electrolyte membrane fuel cells (PEMFCs) are the favored design applied to smaller stationary systems. In the next century there will be a visible shift in the market from centralized power to distributed power. In the past economies of scale directed power production systems towards large centralized units located away from the urban areas. FC systems are used to provide the various energy forms required by an urban infrastructure, such as heating, cooling and power and subsequently this increases the FC efficiency as all by-products of the fuel cell system are utilized effectively [16].

Another favorable fuel cell used in stationary power is the Solid Oxide Fuel Cell (SOFC) as it has a very good overall efficiency and it produces a high quality exhaust heat [17]. This heat is often used to increase the system efficiency even higher when the high temperature exhaust gases are expanded within a gas turbine. The efficiency can then be increased up to 70% with appropriate integration into a CHP system. An example of such a system can be seen in Figure 2-5.

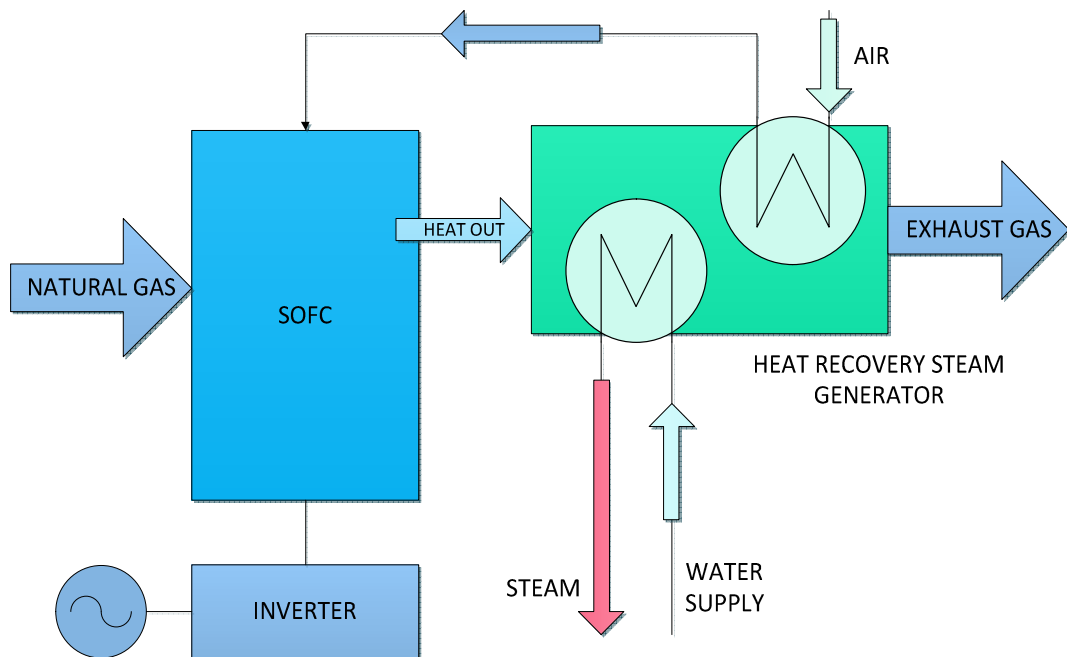


Figure 2-5 CHP System with a Solid Oxide Fuel Cell

The temperature of the network can be adapted to suit the season; the coefficient of performance (COP) of the heat pump reaches its highest value in summer when the temperature corresponds only to domestic hot water requirements. The amount of heat recovered is derived from the knowledge of the water and gas enthalpies at the entrance of the heat exchanger [17].

2.3 Fuelling a Fuel Cell

Primarily fuel cells use pure hydrogen as their source of fuel. Methane and carbon monoxide can also be used as these two sources are hydrogen carriers. Reactions within the fuel cell system convert these gases in to the necessary hydrogen [18].

In the universe, hydrogen is the most plentiful element. Despite this abundance, it does not appear naturally in a useful form. Approximately half of the world's hydrogen supply is manufactured through the steam reforming of natural gas. This will probably provide the earliest affordable feedstock of hydrogen, however today's costs are excessively expensive [14]. Research is currently being conducted to develop alternate methods of hydrogen production, which are more economically viable see Figure 2-6.

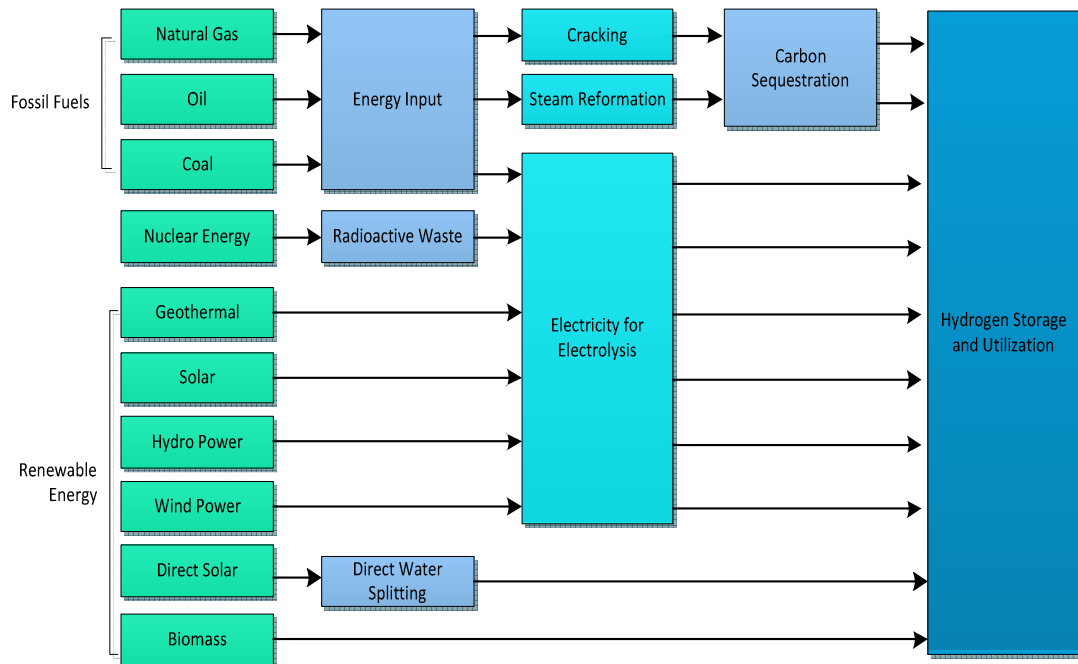


Figure 2-6 Methods of Hydrogen Production

Over the next 10 to 30 years hydrogen will most likely be produced from fossil fuel sources. The long-term solution to hydrogen production will likely be biological, nuclear, or biomass sources. Despite this research, hydrogen is still expensive and a pollution creating process.

Fuel	Cost per million British thermal units (BTU)
Hydrogen	\$30
Natural Gas	\$3
Gasoline	\$9

Table 2-2 Comparison of Fuel Production Costs

Table 2-2 lists a rough estimate of cost per million BTU for three fuel types [11]. The Table shows that Hydrogen is 3 times more expensive compared to gasoline and 10 times more expensive compared to the cost for natural gas. Until these production costs can be reduced, another option is to use a natural gas as a hydrogen carrier, see

Table 2-3. These carriers are either natural sources of hydrogen or are produced through a variety of industrial processes.

	H_2 Hydrogen	CH_4 Methane	NH_3 Ammonia	CH_3OH Methanol	C_2H_5OH Ethanol	C_8H_{18} Octane
Molecular Weight	2.016	16.04	17.03	32.04	46.07	114.2
Freezing Point (°C)	-259.2	-182.5	-77.7	-97.8	-117.3	-56.8
Boiling Point (°C)	-252.77	-161.5	-33.4	64.7	78.5	125.7
Enthalpy (at 25°C) (kJ/mol)	241.8	802.5	316.3	638.5	1275.9	5512
Heat of Vaporisation (kJ/kg)	445.6	510	1371	1100	855	368.1
Liquid Density (kg/l)	77	425	674	792	789	702

Table 2-3 Properties of Hydrogen Rich Fuels

2.3.1 Hydrogen Production from Natural Gas

Hydrogen is currently produced in industry for a variety of reasons, and occasionally as a by-product of other processes. One such process is steam reforming of natural gas. In this process the hydrocarbon and steam are run through a catalytic cycle where hydrogen and carbon oxides are released [13]. This method is most efficiently used with light hydrocarbons such as methane and naphtha. The process can be seen below in Figure 2-7.

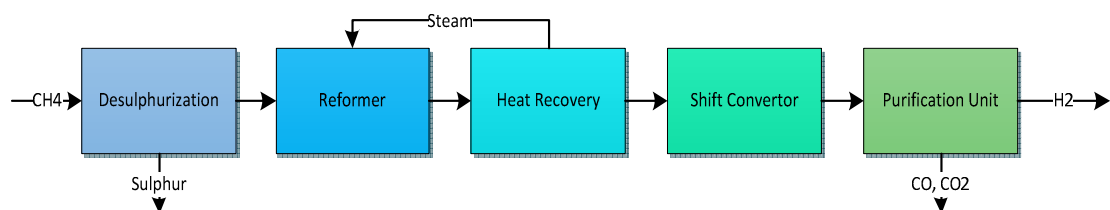
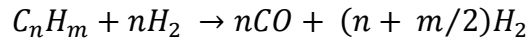


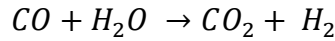
Figure 2-7 Steam Reforming Process

The process includes a desulphurization phase as a requirement for fuel cells. Sulphur, in the form H_2S is a major inhibitor of performance.

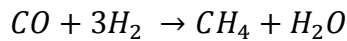
The ideal reformer process's governing equations are as follows.



equation 2-5



equation 2-6



equation 2-7

The overall reaction is endothermic and therefore requires external energy to be supplied to the system [11]. By heating the process at about 800°C the conversion of methane is about 98%, and the hydrogen production is about 72%. Subsequently a reforming furnace must be used to supply the heat to the system.

2.3.2 Hydrogen Production from Coal Gas

Coal is a non-renewable resource, but it is abundant with well know properties. This source of hydrogen production is a potentially huge market. In coal gasification the coal is burned. The reactant gases produced are joined with steam (this is also generated by the burning coal). The mixture of coal and steam passes through a series of chemical reactions. This subsequently produces hydrogen and carbon dioxide. This process requires very high temperatures for the rate of reaction to be sufficient.

Since coal is not perfect carbon there can be deviations from this process. The derivations vary according to where the coal came from and the quality of the coal. If there is ash, sulphur content, and the tendency to agglomerate in the coal it makes the coal gasification process very difficult and complex, inhibiting the efficiency.

2.4 Hydrogen Production from Bio Fuels

Bio-fuels are derived from a natural organic material and can include plant mass, wood, algae, vegetable mass, animal waste and animal tissue and municipal waste (landfills).

Biomass can be converted into energy in several ways; direct combustion, conversion to biogas, conversion to ethanol, conversion to methanol, and finally conversion to liquid hydrocarbons [2]. In order to effectively use biomass to produce hydrogen there are two major processes; anaerobic digesters and pyrolysis gasifier. An anaerobic digester (AD) is a process that converts complex animal matter (manure) into simpler gases (methane). Further development of this technology would be beneficial to the fuel cell industry. Pyrolysis gasification is a process of thermal decomposition to produce gases (methane). This process is only efficient in large-scale production.

2.5 Hydrogen Production for Automotive Applications

For significant long-term adoption of hydrogen fuelled vehicles manufacturers must successfully agree on how the vehicles will be fuelled. The topic of fuelling the fuel cell has motivated much of the recent drive to develop hydrogen fuel cell technology. To use pure hydrogen in a fuel cell it must first be produced, or reformed, from other compounds or processes. The differences in production process, origin and storage of hydrogen must be standardized by the industry before auto fuel cells become commercially possible [19].

2.6 Fuel Storage

2.6.1 Compressed Gas

Compressed gas storage is simplest approach to hydrogen storage. The technical problems are widely understood and thus the process is mostly optimized. This is however not very efficient and would not make a good choice for long-range vehicular storage. In compressed gas storage the hydrogen is held in containers at pressures near 200 bar. As hydrogen has such a low density it is very difficult to store, even under these high pressures. A typical

steel cylinder at 200 bar stores only 0.036 kg of hydrogen per 3.0 kg of tank mass [2]. The material of the tank must also be considered as hydrogen is very small and can escape through the lattice of some metals. This material must also be resistant to hydrogen embrittlement which occurs when the hydrogen propagates into the metal creating blisters and promoting crack propagation. Storage of hydrogen in tanks for automotive applications is currently used in a number of hydrogen powered buses (see Figure 2-8). Tanks are often located on the roof of the bus.



Figure 2-8 Toyota FCHV Bus (Expo 2005 Aichi Japan specification)³

2.6.2 Cryogenic Liquid

Another feasible technology for hydrogen storage is to cryogenically freeze the gas before converting it into a liquid state (LH_2). This is a costly option as the gas must be pressurised and held at 22K (-251.15°C). It is currently the only possible way to store large amounts of hydrogen. This method of storage has also been explored by BMW for its possible use in cars. BMW has developed a hydrogen internal combustion engine that runs on liquid hydrogen. The liquid hydrogen is stored on board in a 50 kg container which holds 120 litres (8.5 kg) of LH_2 [17].

In cryogenic storage liquid hydrogen must be preheated, usually by a heat exchanger, before it is used as it is not possible to use liquid fuel in a fuel cell.

³ Photo from http://en.wikipedia.org/wiki/Fuel_cell_bus

Again, BMW operate several company cars on liquid hydrogen stations demonstrating it is possible to build an infrastructure on LH_2 .

Safety issues that need to be considered with the use of liquid hydrogen include

- Possibility of severe frostbite
- It is necessary to insulate all surfaces to prevent the liquid from boiling.
- It is necessary to insulate all surfaces to prevent liquid air forming which is very combustible.

2.6.3 Other options for hydrogen storage

There are other technologies for the storage of hydrogen for example as metal hydrides and nanotubes. However these are not seen as possible uses in the near future as metal hydrides are simply too heavy and nanotube technology is too new and some evidence even suggests that it is faulty.

2.7 Barriers to Market

Fuel cells have numerous problems that must be solved before economically implementing the technology into society. These challenges are demonstrated below.

2.7.1 Cost Reductions

Cost reductions are essential to make fuel cells comparable in cost to other technologies. The cost of fuel cells is currently too high to allow them to become an economically effective alternative. As with any commercially available product, their cost will decrease once high volume production begins.

Table 2-4 shows the equivalent miles per gallon (mpg) for four fuel cell system combinations. These are similar gasoline vehicles however with the potential saving on the cost of the fuel itself hydrogen is the cost efficient choice.

Air Control/System Configuration Case	Fuel Economy (mpg equivalent gasoline)	Hydrogen Used (kg)
Ideal air control with expander	43.34	0.2454
Ideal air controller without expander	40.85	0.2630
No air control with expander	34.48	0.3081
No air control without expander	26.81	0.3959

Table 2-4 Warm Start Fuel Economies and Usage for Various Air Control Cases

The market place will not adopt technology that is not economically beneficial and until fuel cells can decrease their overall running cost the public will endure to use internal combustion engines for automotive purposes. This can currently be seen with Nissans launch of the Leaf and its low initial sales due to its high purchase cost and additional charging infrastructure required. The high capital cost of fuel cells is their most significant limiting factor in the widespread implementation of fuel cells in society. Significant work is currently taking place towards reducing the costs associated with fuel cells. Cost reductions specifically being researched in material volume reduction, lower-cost material alternatives, reducing complexity in integrated systems, minimizing temperature constraints, streamlining manufacturing processes, increasing power density (footprint reduction) and scaling up production gaining the benefit of economies of scale [20-27].

2.7.2 Reliability

Reliability of fuel cells is another area which must be improved so to prolong the life of the fuel cells and demonstrate that they are capable of providing power continuously for extended periods of time. If fuel cells can demonstrate to have higher reliability and power quality they have the potential to be a competitive source of power. Fuel cells can provide high-quality power which is advantageous in certain applications.

Fuel cell research has validated their ability to provide exceedingly efficient electricity and with notable sensitivity to the environment. However the long-term reliability and performance of some fuel cell systems has yet to be verified. The specific research and development issues encountered include [28]

- Durability and life span,
- Thermal cycling proficiency,
- Endurance in installed environment (for example transportation effects)
- Performance connected to the grid.

Further research is required before adoption into the market.

2.7.3 System Integration

Real examples of fuel cells and the results of such implementation should be demonstrated to gain the public's interest. The success of fuel cells relies on two key systems integration issues. Firstly the "development and demonstration of integrated systems in grid connected and transportation applications" and secondly "the development and demonstration of hybrid systems at achieving very high efficiencies"[28]. Both issues will help minimise the cost of electricity produced.

The world's first hydrogen and electricity co-production unit is located in Las Vegas. Air Products and Chemicals Inc. built this facility in 2002 in partnership with Plug Power Inc., the U.S. Department of Energy, and the City of Las Vegas. The unit demonstrates hydrogen as a safe and clean alternative fuel for automotive applications [29].

2.7.4 Safety

Hydrogen intrinsically carries no more risk than other conventional fuels, such as natural gas or gasoline. The main safety concern with the adoption of fuel cells in the market is the perceived safety resulting from well-known disasters such as the Hindenburg [30]. If two vehicles (one petrol and one hydrogen fuelled) were involved in an accident resulting in fire the hydrogen would burn quickly, cleanly and upwards as the gas is light. Hydrogen needs oxygen to burn; therefore combustion within a hydrogen tank is impossible. In event of a leak, the characteristics of hydrogen would mean the gas would quickly diffuse and rise, removing the gas from the source of the leak.

Table 2-5 shows a comparison of the stored energy in both fuels [31].

	Hydrogen (Riversimple)	Gasoline
Energy Density (MJ/kg)	120	44.4
On Board Fuel Stored (kg)	1	30 (approx. 40 litres)
Total Energy Stored (MJ)	120	1332

Table 2-5 Comparison of the Energy Stored in Hydrogen and Gasoline

It is evident that the energy stored on board the hydrogen vehicle is roughly a tenth of a standard gasoline vehicle. Additionally composite hydrogen tanks are considerably stronger than a polyethylene petrol tank, making the risk of rupture considerably lower. Hydrogen fires have much lower levels of radiant heat in comparison to hydrocarbon fires. This significantly reduces the risk of secondary fires. The petrol vehicle would however engulf the full vehicle leaving little remaining once the flames had subsided, see Figure 2-9.



Figure 2-9 (1) 3 seconds after ignition (2) 1 minute after ignition and (3) 1.5 minutes after ignition.⁴

A significant amount of work is needed to ensure the public perception of hydrogen safety is truthful.

2.7.5 Infrastructure

One hurdle left to overcome is how to get the hydrogen, or some hydrogen rich fuel, to the fuel cell. This inevitably means developing a hydrogen infrastructure. A project of this scale would cost millions of pounds and would take a huge commitment by the government and industry. This must be solved before the fuel cell can achieve wide spread market acceptance.

⁴Photo from <http://www.fuelcelltoday.com/analysis/analyst-views/2012/12-07-18-perceptions-of-hydrogen-fuelling-safety>

An example of where this is currently underway is the US governments vision is to have affordable vehicles that are not dependent on foreign oil and free of harmful emissions. This objective must be achieved without compromising on safety, freedom of mobility or vehicle choice [29]. The main pillars for the programme are.

- Freedom from petroleum dependence
- Freedom from pollutant emissions
- Freedom to choose the vehicle you want
- Freedom to drive where you want, when you want
- Freedom to obtain fuel affordably and conveniently

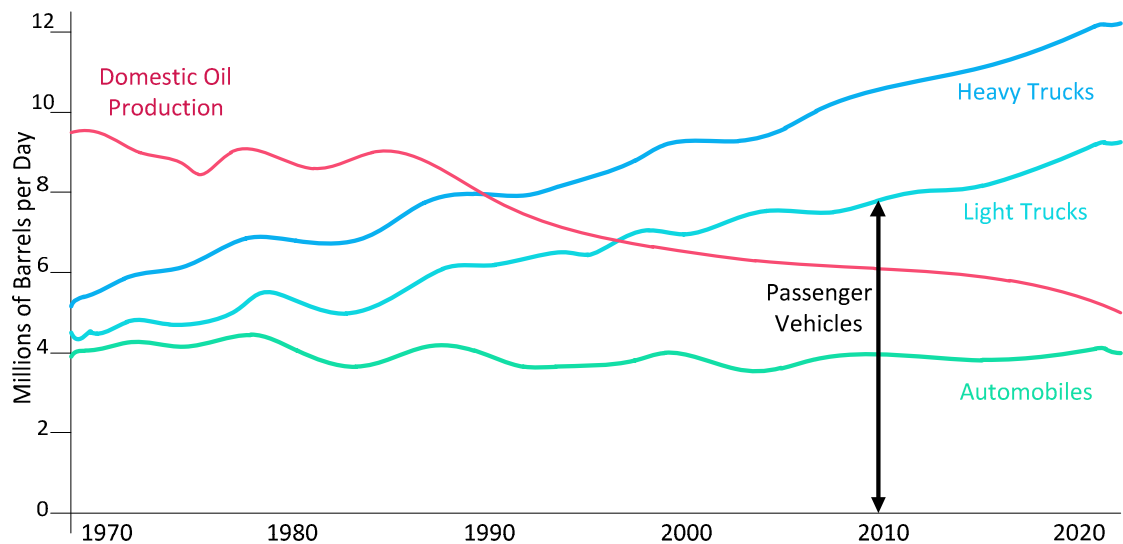


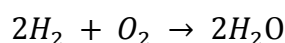
Figure 2-10 Petroleum use by Vehicles in the USA

The steady increase in importing oil in order to meet the demand for petroleum products is politically problematic and not maintainable in the long term (see Figure 2-10). This trend cannot be significantly changed by focussing efforts on one economic sector. Changing this consumption pattern requires a multi-faceted approach, including policy change, research programs across every end use area of the economy with the transport sector having an important role to play.

Chapter 3. Fuel Cell Systems

3.1 Introduction

Fuel cells are excellent energy sources, providing dependable power at steady state. However they struggle to respond to electrical load transients as quickly as required. This is for the most part due to their slow internal electrochemical and thermodynamic responses [12]. The basic chemical process a fuel cell works on is combustion of hydrogen in the simple reaction



equation 3-1

Electrical energy is generated instead of releasing the energy in a wasteful form such as heat. The first demonstration of a fuel cell was by William Grove in 1839 [2]. In this experiment he found that when a power supply was attached in series, the water separated into its components of hydrogen and oxygen. When the power supply was removed and replaced with an ammeter a small current could be seen.

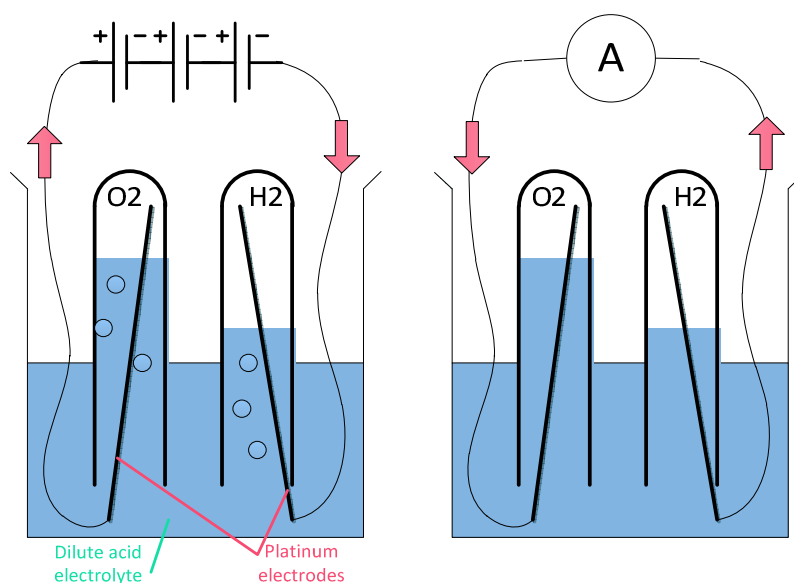


Figure 3-1 William Grove Experiment

This was due to the oxygen and hydrogen recombining. The current in the original experiment was very small due to the small 'contact area' between the gas, the electrode and the electrolyte. The small current could also be attributed to the great distance between the electrodes.

To get over these problems in subsequent experiments the electrodes were changed to a flat design and a thin layer of electrolyte used to give the greatest available contact area between the electrode, the electrolyte and the gas.

In order for the electrolyte and gas to penetrate the structure of the electrode it is made porous. This maximizes the contact area between the electrode, the electrolyte and the gas. To understand how an electric current is produced by the reaction and where the electrons come from, the individual reactions taking place at each electrode need to be considered. The reaction is different for different types of fuel cells.

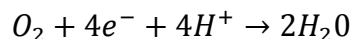
3.2 Acid Electrolyte Fuel Cell

The acid electrolyte fuel cell is the simplest and most common fuel cell. At the anode (the negative terminal) the hydrogen gas ionizes and releases electrons. This creates H^+ ions (or protons) and this reaction releases energy



equation 3-2

At the cathode (the positive terminal), oxygen reacts with the electrons taken from the electrode. This also reacts with the H^+ ions giving water.



equation 3-3

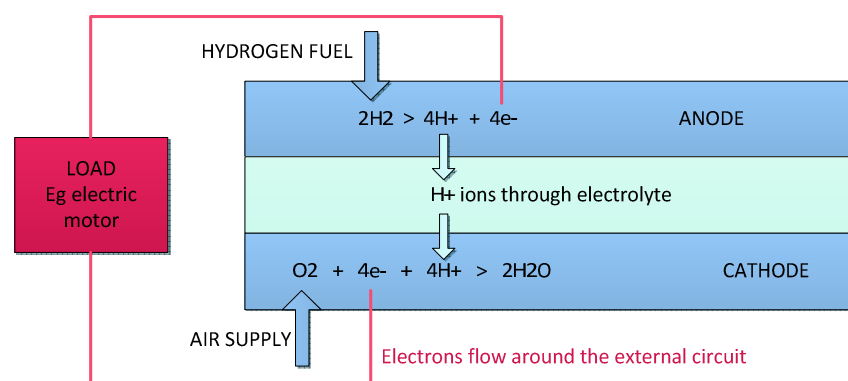


Figure 3-2 Current Flow in an Acid Electrolyte Fuel Cell

The electrons released at the anode must travel through an electrical circuit to the cathode for both these reactions to proceed continuously. The H^+ ions (or protons) must go through the electrolyte and this must only allow H^+ ions to

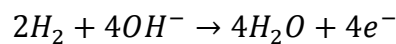
pass through it. If it allowed electrons to pass through then they would go through the electrolyte and not the external circuit as the electrons take the path of least resistance. An acid is a fluid with free H^+ ions so allows free flow of protons. Polymers can also be made to contain mobile H^+ ions. These are called proton exchange membranes and are the most common fuel cell.

3.3 Alkaline Electrolyte Fuel Cell

The overall reaction is the same in an alkaline electrolyte fuel cell but the reactions taking place at each electrode differs. In this case hydroxyl (OH^-) ions are available and mobile [32].

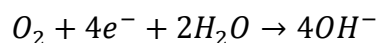
The OH^- ions must be able to pass through the electrolyte for the reactions to proceed continuously. There must also be an electrical circuit for the electrons to travel from the anode to the cathode. As you can see from equation 3-4, double the amount of hydrogen is needed as oxygen for the reactions to take place.

At the anode



equation 3-4

At the cathode



equation 3-5

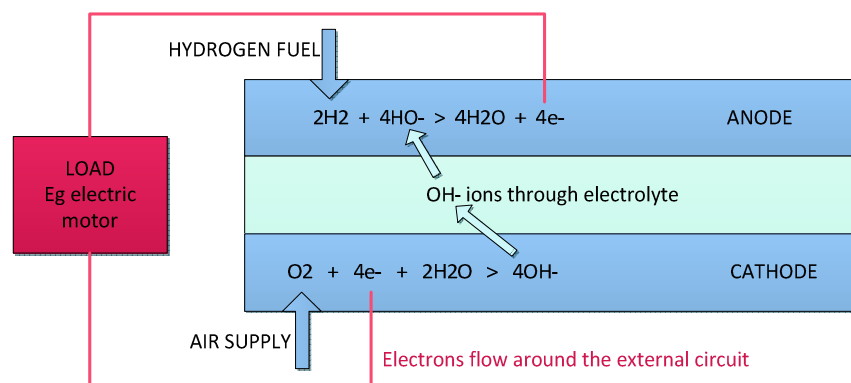


Figure 3-3 Current Flow in an Alkaline Electrolyte Fuel Cell

The basic structure of a fuel cell comprises of an electrolyte layer which is 'sandwiched' in contact with a porous anode and cathode. The dimensions and materials, which are used each have an effect on how much current can be produced [33].

3.4 Limitations on current production

Before any electrical energy can be exorcised the activation energy must be delivered. The reaction has a classic energy form as shown in the following diagram.

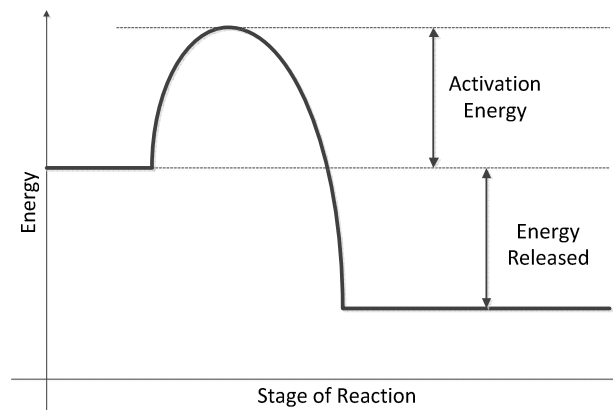


Figure 3-4 Energy diagram for a simple exothermic chemical reaction

In fuel cells the molecules have a low amount of energy so, if left untouched, the reaction would only proceed slowly. Inclusion of a catalyst, increasing the temperature or the electrode area will in turn increase the reaction rate. Increasing the temperature or introduction of a catalyst can be applied to any chemical reaction, however increasing the electrode area is very important and applies only to fuel cells. Fuel cell design is most commonly stated in terms of current per cm^2 . In order to increase the surface area the electrode is made highly porous. Modern fuel cells have a microstructure that provides them with a surface area that can be hundreds or thousands of times their straight forward length by width.

3.5 The Basic Construction of a Fuel Cell.

The joining of H_2 fuel and OH^- must take place on the surface of the electrode. This is where the electrons are removed

3.5.1 The Bipolar Plate

The voltage of a single fuel cell is relatively small and as such many have to be connected in series to produce a useful voltage. This assembly of cells is known as a stack. Cells are connected within the stack using a bipolar plate. This makes links all over the surface of one cathode and the anode of the next cell. The bipolar plate also feeds oxygen to the cathode and fuel gas to the anode. A reliable electrical connection must be made by the two electrodes and the gas supplies are to remain strictly separated.

The bipolar plates consist of horizontal grooves on one side and vertical grooves on the other as shown in Figure 3-5 below.

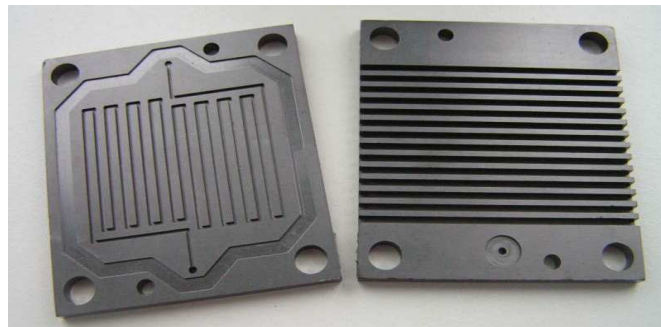


Figure 3-5 Two bipolar plates showing both sides⁵.

The grooved plates are manufactured from a good conductor such as graphite or stainless steel. The channels allow the gases to flow over the face of the electrodes; at the same time they make a consistent electrical contact with the surface of each alternate electrode.

⁵ Photo from <http://image.made-in-china.com/2f0j00oestlwLnnUpP/Graphite-Bipolar-Plate.jpg>

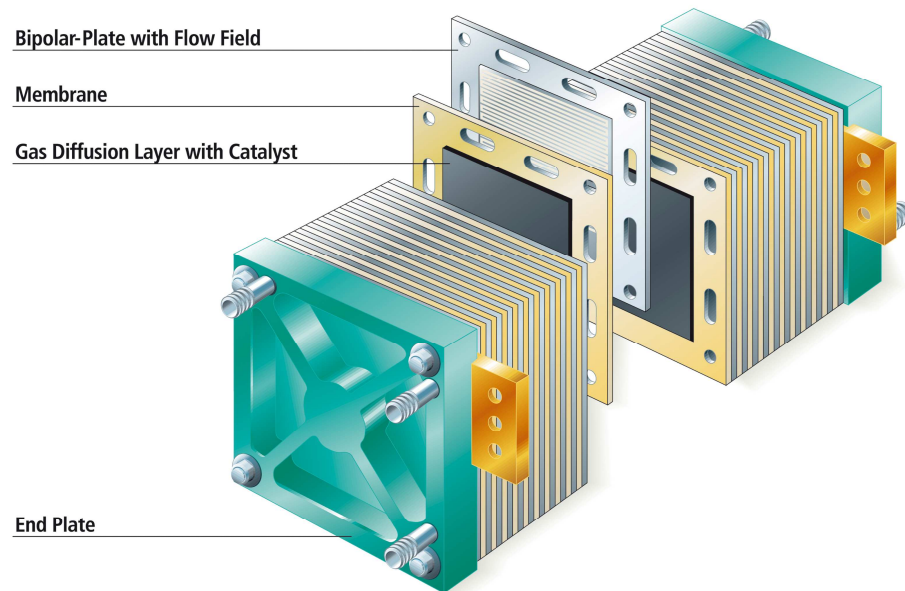


Figure 3-6 Fuel Cell Stack⁶

Vertical channels in the stack feed the hydrogen over the anodes while horizontal channels supply oxygen (or air) over the cathodes. From the outside the stack appears to be a solid block. The electric current passes efficiently straight through the cells, rather than over the surface of each electrode one by one. The structure is strong and tough with the electrodes well supported. Ideally the bipolar plate should be as thin as possible to reduce electrical resistance and to make the fuel cell stacks small. This however makes the channels for the gas flow narrow; making it more difficult to pump the gas around the cell and as such a compromise must be reached.

3.5.2 Gas Supply and Cooling

The problem of supplying the gas and preventing leaks means the design is more intricate. As the electrodes are porous to allow the gas flow through them, they would also allow gases to leak out the edges. As a result the edges of the electrodes must be sealed. This can be achieved by constructing the electrolyte larger than one or both of the electrodes and fitting a sealing gasket around

⁶ Diagram from <https://www.ticonaphotos.com/PL/FuelCell%20Stack%20Graphic%20E%20Ticona.jpg>

each electrode. The oxygen and fuel is then supplied to the electrodes using manifolds as shown in Figure 3-7.

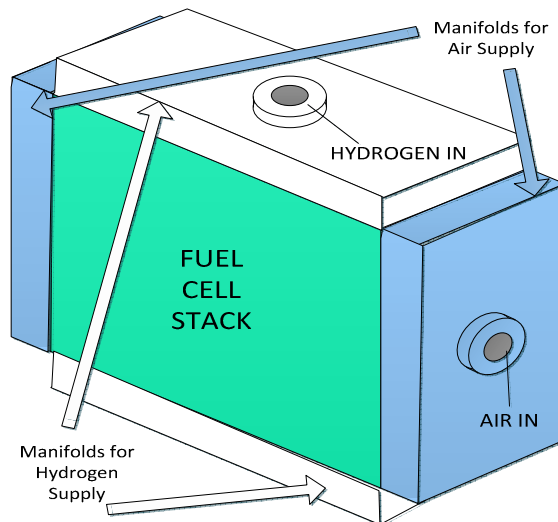


Figure 3-7 External manifolds fitted to the fuel cell stack.

As the edges of the electrodes are now sealed the hydrogen should only interact with the anodes as it is fed vertically through the fuel stack and the oxygen (or air) should only contact the cathodes.

In practice the reactant air passing over the cathodes cools this type of cell and subsequently air has to be provided at a rate higher than demanded by the chemistry. Sometimes this is enough to cool the cell but it is inherently a waste of energy. Additionally the gasket is not pressed firmly onto the electrode at the point where there is a channel therefore there is an increased likelihood of leaks. A more common arrangement incorporates large bipolar plates which allow additional channels through the stack feeding the fuel and oxygen to the electrodes. This type of arrangement is called internal manifolding with the reactant gases fed in where the positive and negative connections are also made.

3.5.3 Internal manifolding

The internal manifold bipolar plate can be cooled in many ways. The simplest is to make narrow channels through the plates and drive cooling air or water through them. Alternatively channels can be produced along the length of the cell. The preferred method differs greatly with the different fuel cells.

3.6 Efficiency of a Fuel Cell

In a fuel cell it is not obvious what form of energy is being changed into electricity. This means fuel cell efficiency cannot be analyzed the same as a thermodynamic system using Carnot efficiency.

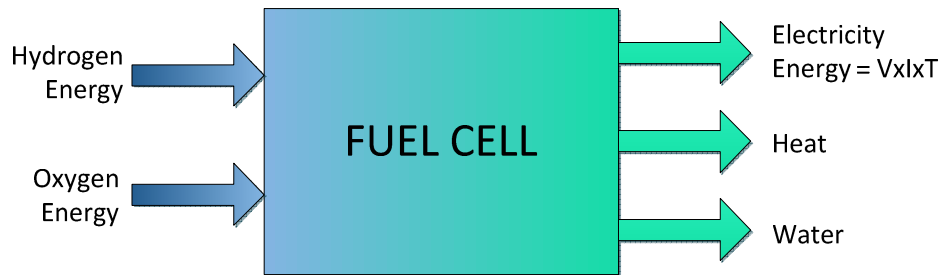


Figure 3-8 Basic Fuel Cell Inputs and Outputs

To calculate the energy changes in the fuel cell one must use “Gibbs free energy”. This is the “energy available to do external work, neglecting any work done by changes in pressure and volume” [2].

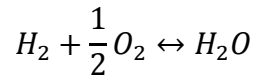
Gibbs free energy is not a constant and differs with temperature and the products state.

Table 3-1 shows Gibbs free energy Δg_f of water at different temperatures and its corresponding efficiency.

Form of Water Product	Temp (°C)	Δg_f (kJ/mole)	Max EMF (V)	Efficiency Limit (%)
Liquid	25	-237.2	1.23	83
Liquid	80	-228.2	1.18	80
Gas	100	-225.3	1.17	79
Gas	200	-220.3	1.14	77
Gas	400	-210.3	1.09	74
Gas	600	-199.6	1.04	70
Gas	800	-188.6	0.98	66
Gas	1000	-177.4	0.92	62

Table 3-1 Gibbs Free Energy of Water

As discussed previously the chemical change in a hydrogen fuel cell can simply be shown as follows



equation 3-6

Assuming that the chemical change is reversible then all Gibbs free energy is converted into electrical energy. Subsequently the open circuit voltage of the fuel cell can be found using the Gibbs free energy.

The charge produced by each reaction is

$$-2Ne = -F \text{ (Coulombs)}$$

equation 3-7

Where F is Faraday constant in and N is Avogadro's number

Therefore the electrical work done within the fuel cell by moving 2 electrons around the circuit is as follows.

$$\begin{aligned} \text{Electrical work done} &= \text{charge} \times \text{voltage} \\ &= 2FE \text{ (Joules)} \end{aligned}$$

equation 3-8

Where E is the voltage of the fuel cell in volts

The electrical work done is equal to the Gibbs free energy released Δg_f , which means this equation then becomes

$$\Delta g_f = -2FE$$

equation 3-9

This can be rearranged to give the reversible open circuit voltage for a hydrogen fuel cell

$$E = \frac{-\Delta g_f}{2F}$$

equation 3-10

The efficiency in the fuel cell can be calculated if it is known how much energy is produced if the fuel were simply burnt and not used to fuel this reaction. This value is known as the "enthalpy of formation Δh_f ", or more commonly as the calorific value.

$$\frac{\text{electrical energy produced per mole of fuel}}{-\Delta h_f} = \frac{\Delta g_f}{\Delta h_f}$$

equation 3-11

The enthalpy of formation depends on the state of the H₂O product in the governing combustion equation and can be in the form of either steam or liquid.

For steam $\Delta h_f = 241.83\text{kJ/mole}$ (higher heating value of H₂O)

For liquid $\Delta h_f = 285.84\text{kJ/mole}$ (lower heating value of H₂O)

The maximum efficiency of the fuel cell is simply the actual energy produced by the reaction divided by the ideal energy produced by the reaction. These efficiencies can also be seen in

Table 3-1.

$$\text{Maximum efficiency possible} = \frac{\Delta g_f}{\Delta h_f} \times 100\%$$

equation 3-12

Even though the fuel is converted more efficiently at lower temperatures the voltage losses are much less in higher temperature fuel cells. It is therefore more advantageous to run a fuel cell at a lower efficiency but higher temperature in order to produce higher operating voltages. When the fuel cell is run at higher temperatures the heat generated can be harnessed and recycled more efficiently than the heat generated in low temperature fuel cells.

The efficiency of a fuel cell can also be affected by the pressure and concentration of the fuel. This can be shown using the Nernst equation.

$$E = E^0 + \frac{R_e T}{2F} \ln \left(\frac{\alpha \beta^{\frac{1}{2}}}{\delta} P^{\frac{1}{2}} \right)$$

equation 3-13

$$E = E^0 + \frac{R_e T}{2F} \ln \left(\frac{\alpha \beta^{\frac{1}{2}}}{\delta} \right) + \frac{R_e T}{2F} \ln(P)$$

equation 3-14

Where E^0 is the EMF at standard pressure (V), R_e is Reynolds number, T is Temperature (Kelvin), F is the Faraday constant and P is the Pressure of the system (bar) and α, β, δ are constants that depend on the molar masses and concentrations of H₂, O₂ and H₂O.

equation 3-14 shows that there are many variables to consider when calculating the EMF of a fuel cell, making them complex in analyzing and optimizing. The voltage drop can be determined by assuming that oxygen and water pressures remain unchanged and that the hydrogen pressure changes from P_1 to P_2 as demonstrated in equation 3-15 below.

$$\Delta V = \frac{R_e T}{2F} \ln(P_2) - \frac{R_e T}{2F} \ln(P_1)$$

equation 3-15

$$= \frac{R_e T}{2F} \ln\left(\frac{P_2}{P_1}\right)$$

equation 3-16

3.7 Causes for Voltage Loss

There are four main voltage losses considered in a fuel cell system. Each of these losses has a different effect on the theoretical voltage of the fuel cell and is shown in Figure 3-9.

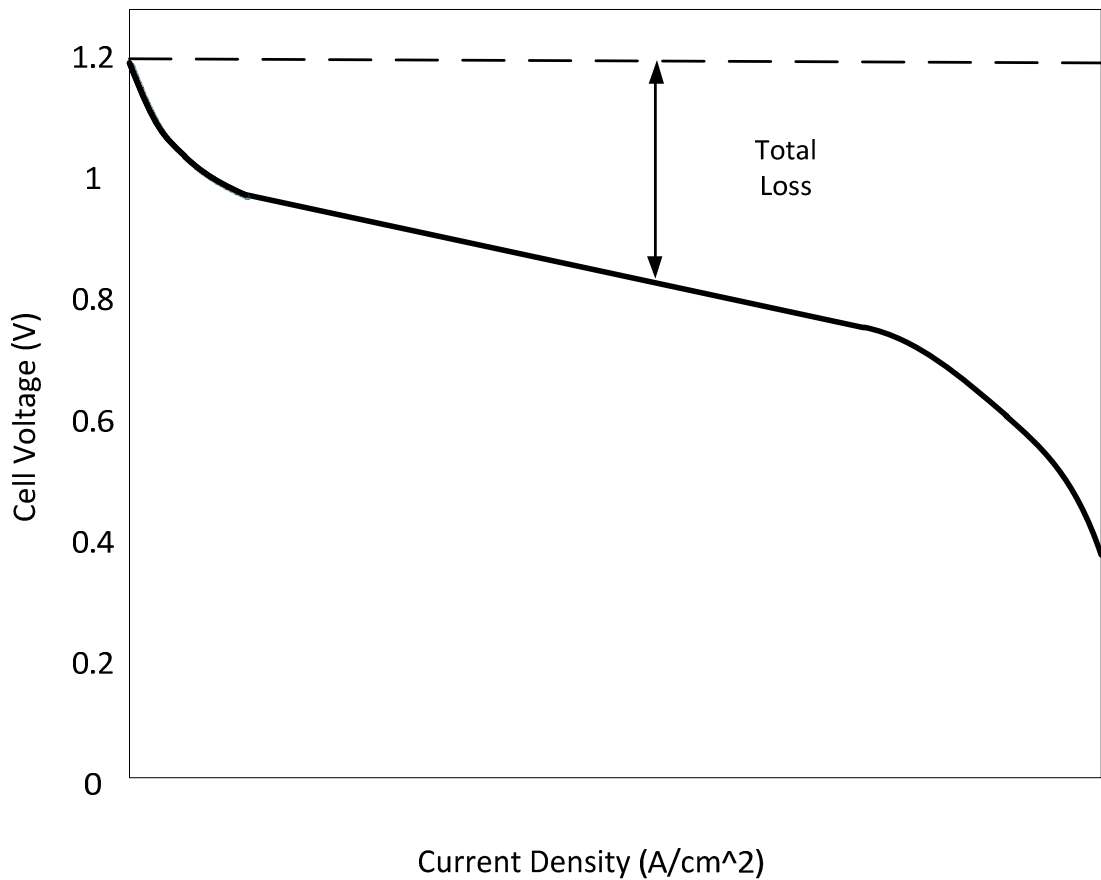


Figure 3-9 Voltage Losses within the Fuel Cell

- **Activation Losses**

This is the initial energy that needs to be put into the system to start the chemical reactions. This loss only occurs in low temperature fuel cells at low current densities.

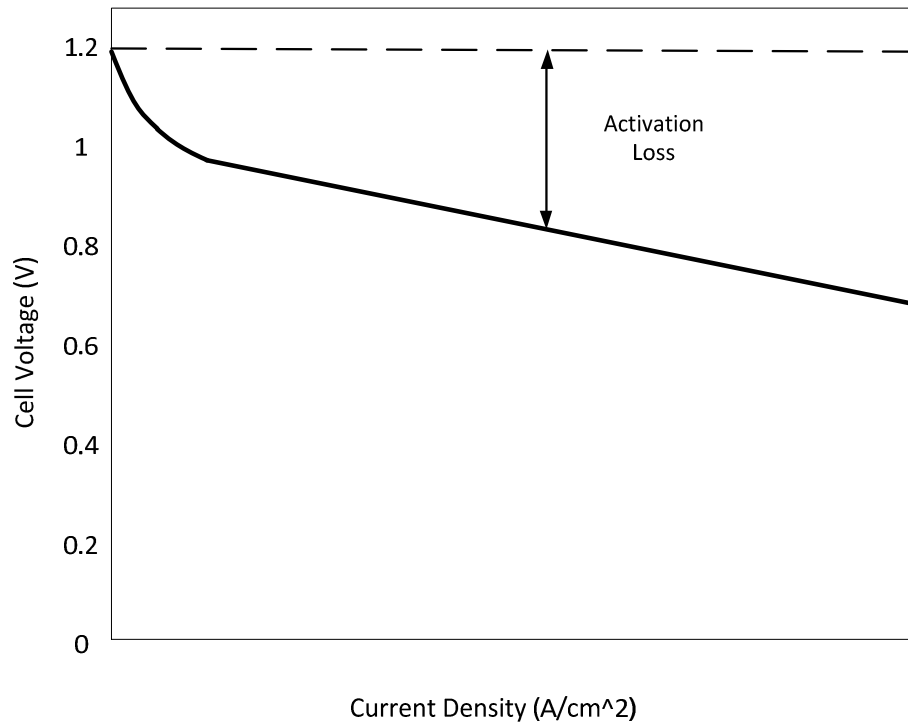


Figure 3-10 Activation Losses within a Fuel Cell

- **Fuel crossover/internal current losses**

These losses are associated with the electrolyte and can occur in two ways; fuel leaking through the electrolyte or electrons leaking through the electrode. This loss only has a substantial effect at low temperatures.

- **Ohmic losses**

These are the most common loss in all electrical devices. This type of loss occurs due to the resistance to the flow of electrons between the anode and the cathode. This loss is directly proportional to the current and is a major cause of losses in both low and high temperature fuel cells.

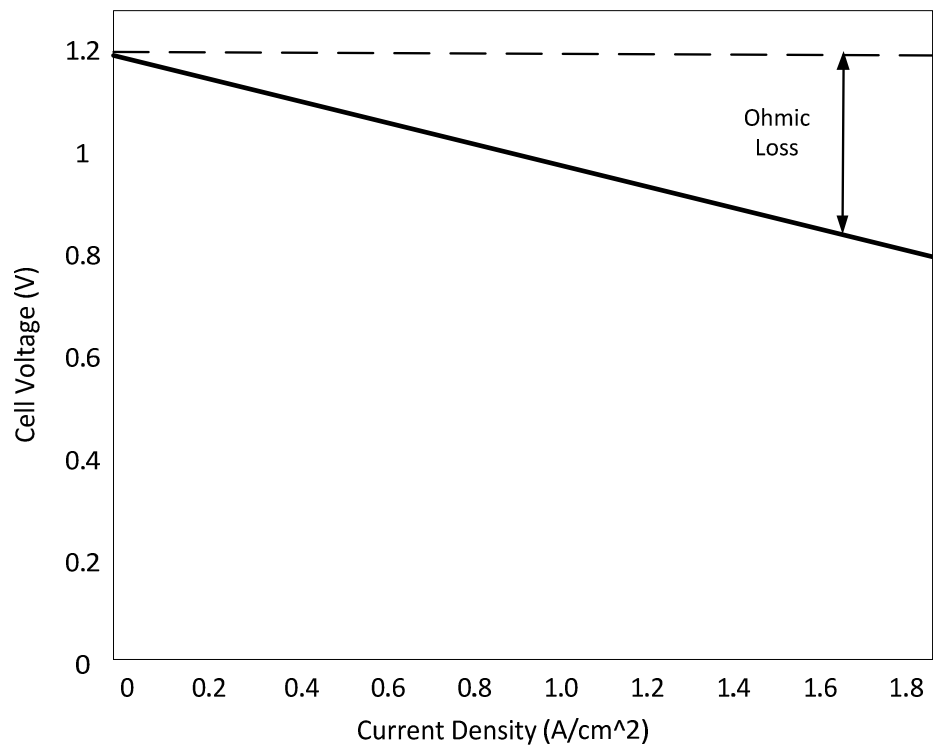


Figure 3-11 Ohmic Losses within a Fuel Cell

- **Mass transport/ concentration losses.**

This occurs in both low and high temperature fuel cells but is only predominant at high current densities. It essentially occurs because the fuel cell is using fuel or oxygen at a higher rate than it can be supplied.

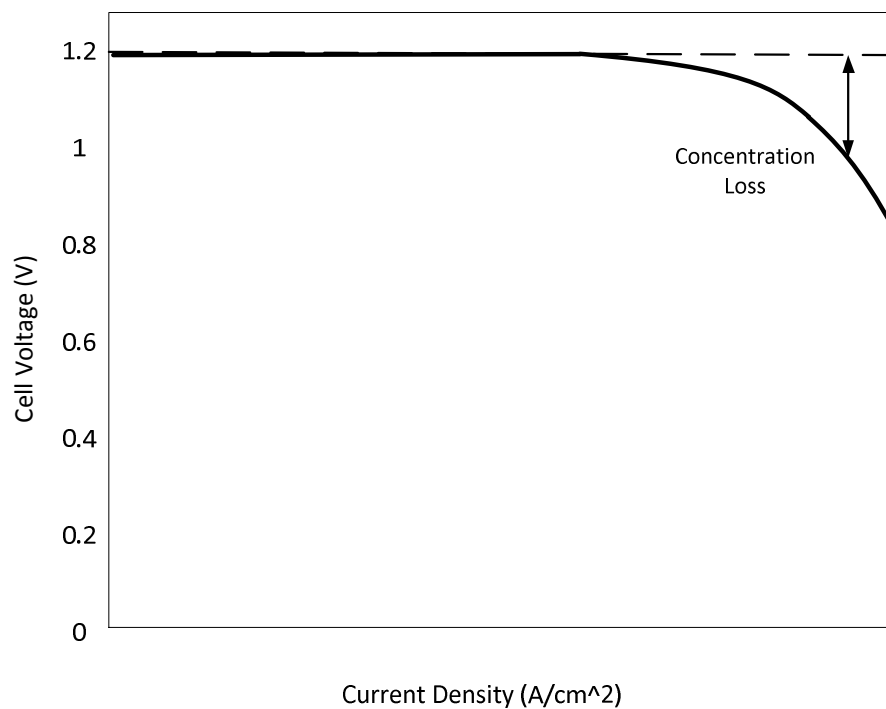


Figure 3-12 Concentration Losses within a Fuel Cell

3.7.1 Activation Losses

The activation losses are the initial voltage losses in low temperature fuel cells. They can be attributed to the energy required to split the hydrogen into electrons and protons, in order for the protons to travel through the electrolyte. This loss is the voltage difference between the two terminals and is often referred to as the “over potential”. Through experimentation Tafel was able to mathematically describe these losses and this is now referred to as the Tafel equation (equation 3-17 and Figure 3-13) [11].

$$E = A \ln \left(\frac{i}{i_0} \right)$$

equation 3-17

Where

$$A = \frac{RT}{2\alpha F}$$

equation 3-18

Where i_0 is the exchange current in amps, R is the ideal gas constant, T is temperature in Kelvin, F is Faradays constant and α the charge transfer coefficient. This value describes the proportion of the electrical energy applied that is harnessed in changing the rate of an electrochemical reaction [2].

The overall value of A is simply a function of the material properties. For typically used materials the value is in a very fine range (approx. 0.5 for the electrode and between 0.1 and 0.5 for the cathode).

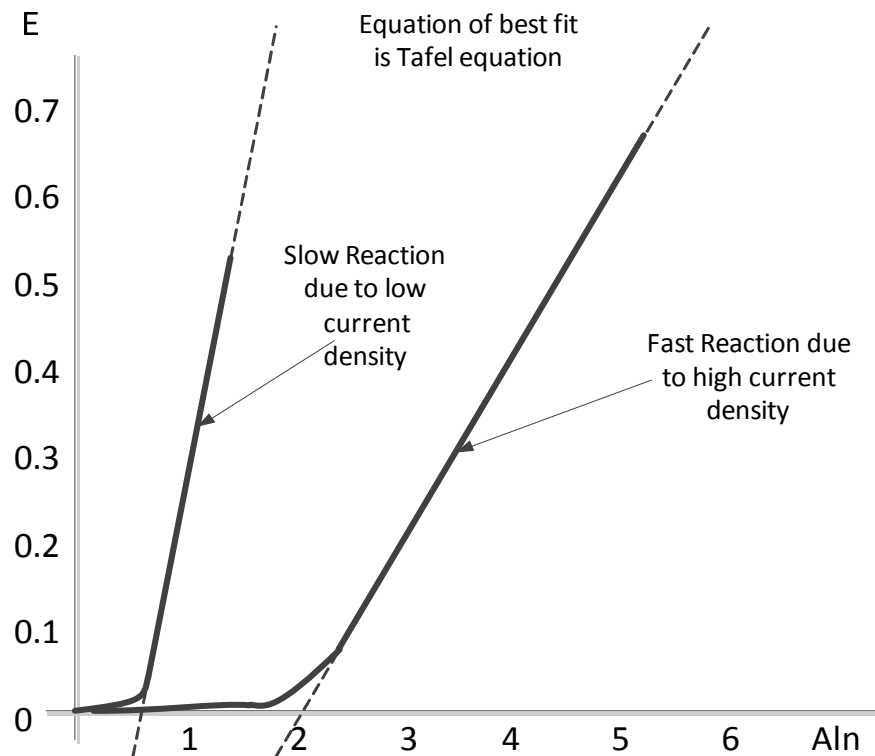


Figure 3-13 Tafel equation

As the aim of fuel cell design is to make the most efficient fuel cell, it is important to minimize the losses. Several steps can be taken in order to minimize the voltage due to activation losses, first of which is increasing the operational temperature. Additionally one can use a catalyst (a rough catalyst increases the surface area over which a reaction can take place or increase the pressure, since the higher the pressure the quicker the reaction will be forced to take place.) Finally a more effective material can be used (see Table 3-2).

Metal	$i_0 \left(\frac{mA}{cm^2} \right)$
Pb	2.5×10^{-13}
Zn	3.0×10^{-11}
Ag	4.0×10^{-7}
Ni	6.0×10^{-6}
Pt	5.0×10^{-4}
Pd	4.0×10^{-3}

Table 3-2 Common i_0 values for Selected Metals

3.7.2 Fuel Crossover/Internal Current Losses

These two sources of voltage loss are grouped together as their losses are both due to the inability to produce the perfect electrode. The electrode can be made from different types of materials considering the type of fuel cells and is either solid or liquid state. The electrode is porous in order to allow proton transfer. However, it is also slightly conductive allowing unreacted fuel and electrons to crossover to the cathode. In both of these processes two electrons are wasted as they are prevented from travelling externally. The Tafel equation can be modified in order to model this phenomenon with the addition of the term

$$i_n \ln \frac{\text{mA}}{\text{cm}^2}.$$

$$E = A \ln \left(\frac{i + i_n}{i_0} \right)$$

equation 3-19

This equation now accounts for the primary loss of voltage in low temperature fuel cells. (In high temperature fuel cells this is not prevalent as the small value of i_n does not significantly change the ratio in the natural logarithm).

3.7.3 Ohmic Losses

These losses occur in the bipolar plates due to the resistance of electron flow. These losses are usually written in terms of current density and area resistance. This makes it easier to evaluate the cell performance, as most cells are rated in terms of current density.

$$E = ir$$

equation 3-20

Where i is the current density in A/cm^2 and r , the area specific resistance.

Using electrodes with extremely high conductivities can reduce the ohmic losses in the fuel cell or decreasing the distance the electrons have to travel as resistance is proportional to distance. A thin electrode would also reduce these losses as the protons would have a shorter distance to travel before combining with the oxygen and electrons.

3.7.4 Mass Transport/Concentration Losses

If the hydrogen is consumed at a substantial rate at the anode then the partial pressure of the hydrogen drops, which in turn slows the reaction rate. This can also occur with the oxygen supply at the cathode. In order to calculate how these losses will affect the voltage, we can introduce the term i_l which represents a limiting current density. It is at this point where the fuel is used up at a rate equal to its maximum speed which it can be supplied. At this point the pressure of excess hydrogen will be zero and there will be no more fuel to increase the current density. Putting this into the ΔV equation earlier gives the overall losses.

$$\Delta E = \frac{RT}{2F} \ln \left(1 - \frac{i}{i_l} \right)$$

equation 3-21

This shows that most of the loss occurs near the limiting factor of i_l . This is also considered a Nernstian loss, as it uses the Nernst equation to determine the voltage change.

3.7.5 Total Fuel Cell Losses

All of the losses discussed can be combined to give an operational graph of the fuel cell. This can be used to determine if a fuel cell is operating at high standards. The equation for the line is

$$\Delta E = E - (i - i_n)r - A \ln \left(\frac{i + i_n}{i_0} \right) + B \ln \left(1 - \frac{i + i_n}{i_l} \right)$$

equation 3-22

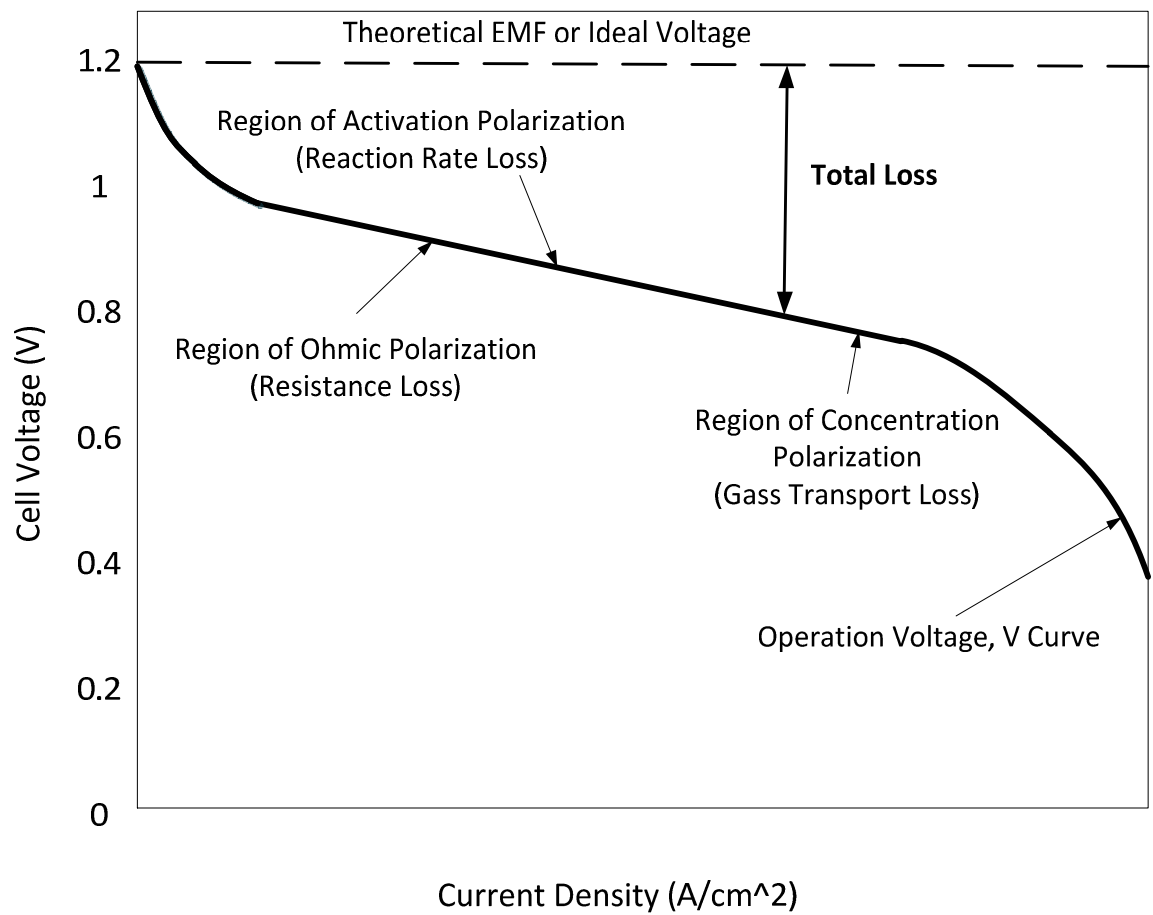


Figure 3-14 Operational Fuel Cell Plot for Voltage vs. Current Density

This graph is often also referred to as the polarization curve and incorporates all the losses discussed.

Chapter 4. The Balance of Plant (BOP)

4.1 Overview

In addition to the stack there are several other components essential for the fuel cell system. There are three key systems essential for the fuel cell. The first, if hydrogen is not supplied as a pure fuel in a tank, is a fuel processing system. This can include a fuel reformer, heat exchangers, chemical reactors, fans and blowers. The air management system controls the flow of air into the fuel cell and consists of a compressor, heat exchangers, humidifier, manifolds and water tank. Finally, the power conditioning system. This consists of a DC/DC converter, batteries and motors. The components required within the balance of plant vary between fuel cell applications.

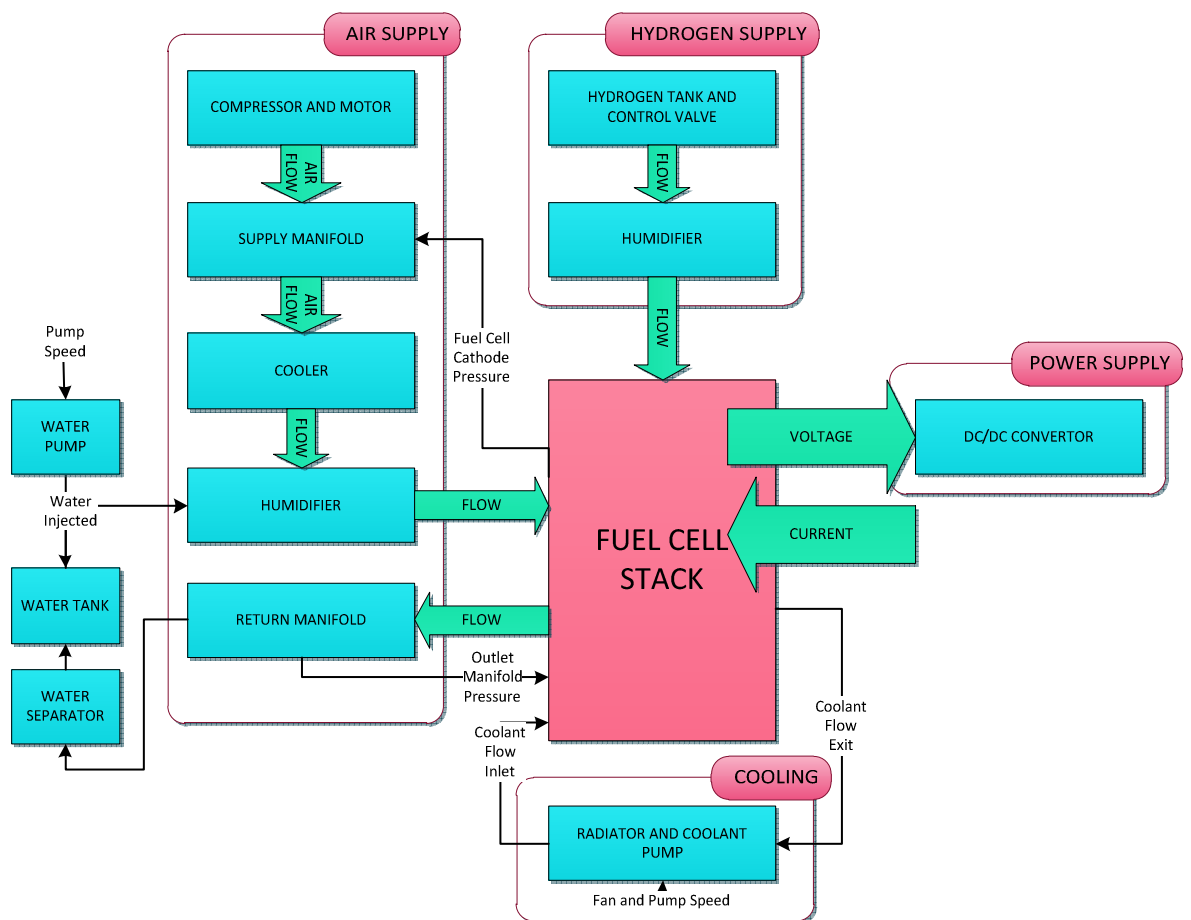


Figure 4-1 Fuel Cell System and its Auxiliaries

4.2 Air supply system

In order to provide oxygen to the cathode and cooling to the system, air must be correctly managed around the fuel cell system. This is achieved through the use of pumps, fans, compressor and blowers. The energy from the exhaust gases can be recovered through the use of turbines reducing wastage and increasing the fuel cell efficiency. The technology for these components is very well developed in other applications, which makes their translation into fuel cell applications an easy process. As fuel cells vary widely in their size and application a wide range of components can be required.

- Compressors – these can differ in type and performance. Different compressors will have different effects on the temperature rise of the gas and will draw varying amounts of power from the fuel cell in order to keep it running at the desired output.
- Fans and Blowers – these are used for cooling and in smaller fuel cells they supply the cathode with sufficient air.
- Turbines – these are used in some fuel cell systems to recycle the exhaust gases and reclaim the energy lost through heat.
- Ejectors – these are simple pumps that can be used for recycling anode gases or circulating hydrogen gas if it comes from a high pressure tank.
- Membrane pumps – these are often used in smaller PEMFCS to pump the reactant air through the system.

Compressors are required in the fuel cell system to increase the pressure of the air supply. Hydrogen is often fed into the system from a high pressure tank whereas the air supply is often just from atmosphere. The air supply must be sufficient to match the hydrogen supply in order for the reaction to take place. Once the air has been compressed it needs to be cooled and humidified before being fed into the fuel cell.

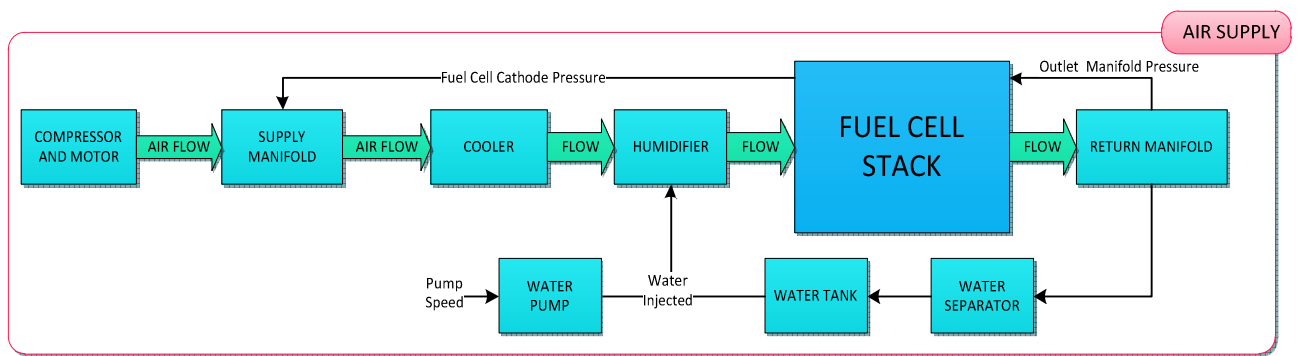


Figure 4-2 Air Supply System

4.3 Hydrogen supply system

In automotive applications the hydrogen is commonly fed to the system from a high pressure tank. Compressed hydrogen is often stored in the magnitude of 350-700 bar, many times greater than the operating pressure of the fuel cell itself. Hydrogen could be fed from an electrolyser however interim tank storage would be required. The pressure of the hydrogen in the tank will vary with respect to how full the tank is. As the tank empties the pressure will decrease. In order to ensure the hydrogen is fed into the fuel cell at the correct rate, a control valve is placed between the tank and the stack. As the demand from the stack increases the valve will open to increase the flow. It is also important that the hydrogen supply does not dry the stack and subsequently a humidifier is also included in the hydrogen supply system.

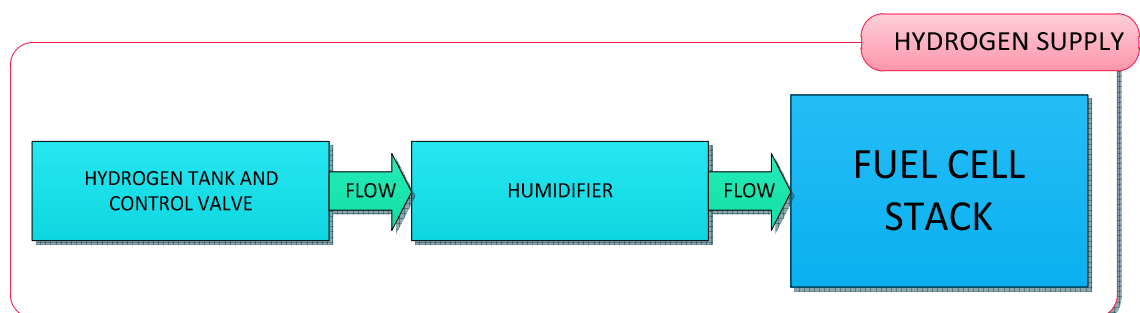


Figure 4-3 Hydrogen Supply System

4.4 Cooling system

PEMFCs operate best at between 80 and 90°C however the temperature of the stack cannot be left unmonitored. The stack must be carefully controlled to make sure it runs at optimum performance and the membrane does not dry out [34]. Once the stack has reached 80°C additional heat must be dissipated to the environment [20]. The cooling system consists of a pump, radiator, air blower and often a water jacket around the fuel cell itself.

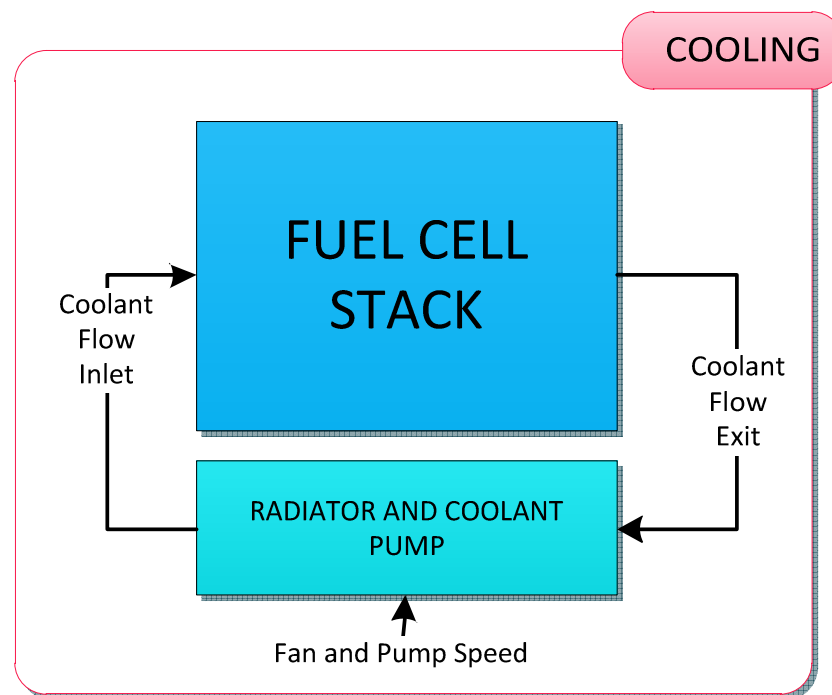


Figure 4-4 Cooling System

4.5 DC-DC Converter

The circuit used to convert a DC voltage from one level to another is a DC-DC converter. A step-down (buck) converter lowers the output voltage and a step-up (boost) converter raises the output voltage. The buck-boost and the cuk are combinations of the two.[35]

A DC-DC converter can also be used to convert an unregulated DC input to a controlled DC output at a desired voltage level. In automotive applications this prevents the drive system from having to cope with a large variation in voltage. Although not all EVs have a DC-DC converter [41], it is widely viewed that the

DC-DC converter is a necessary part of the circuit within a fuel cell system. This is because it keeps the power supply at a constant level rather than transferring the fluctuations of the voltage [36].

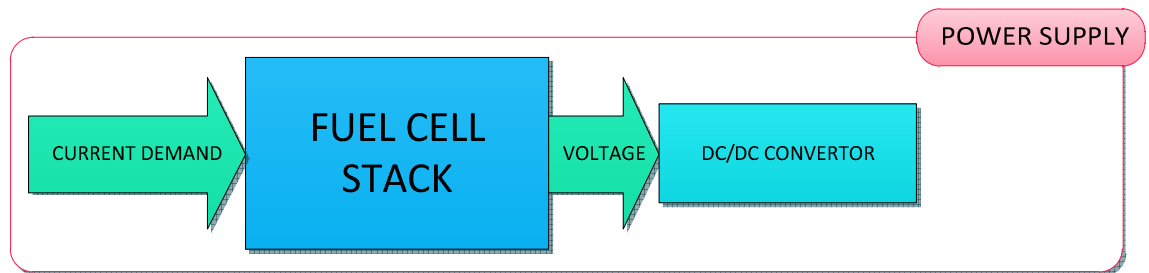


Figure 4-5 DC-DC Converter

Chapter 5. Types of Fuel Cell

5.1 Introduction

There are two fundamental problems with the use of fuel cells. Firstly the slow reaction rates and therefore low currents and power. Additionally hydrogen is not easily available fuel. To solve these problems many types of fuel cells have been trialled.

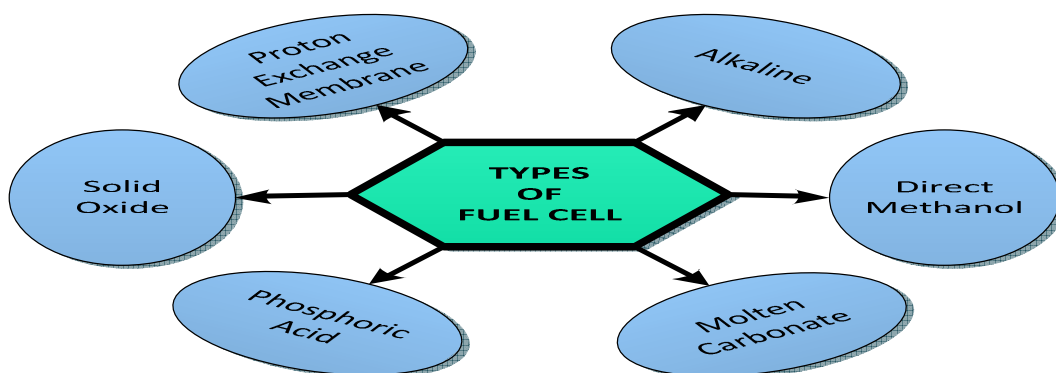


Figure 5-1 Types of Fuel Cell

A brief summary of each of these fuel cells is provided in this chapter. As the PEMFC is the favored fuel cell for automotive applications and subsequently the chosen fuel cell for the VFCS a more in depth explanation is provided.

5.2 Proton Exchange Membrane Fuel Cell (PEMFC)

Common Electrolyte	Operating Temp (°C)	Typical Power Output (kW)	Efficiency	Applications	Advantages	Disadvantages
Perfluoro sulfonic acid	50-100 (typically 80°C)	1-100	60% transport 35% stationary	<ul style="list-style-type: none">- Backup power- Portable power- Distributed generation- Transportation- Speciality vehicles	<ul style="list-style-type: none">- Solid electrolyte reduces corrosion and electrolyte management problems- Low temperature- Quick start-up	<ul style="list-style-type: none">- Expensive catalysts- Sensitive to fuel impurities- Low temperature waste heat

Table 5-1 PEMFC Summary Table⁷

⁷ Table from http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf

The PEMFC is the most commonly used fuel cell in recent developments. The main attraction of the PEMFCs is their ability to operate at very low temperatures. They have the ability to deliver high power densities at this temperature and can be made smaller which reduces overall weight, production cost and specific volume.

The PEMFC consists of three basic parts; the anode, the cathode, and a solid state electrolyte membrane. In most fuel cells these three areas are often manufactured from separate "sheets", and the PEMFC is no exception [11]. The anode and electrode are formed together making a membrane electrode assembly (MEA). Recent advances have made them more economical to develop and research.

The PEMFC has been in use for some time by the US government. It made its debut on the Gemini spacecraft with a life span of only 500 hours. After NASA decided to use alkaline fuel cells on subsequent missions the popularity of PEMFC fell dramatically. PEMFCs are now being actively followed for use in portable applications, automobiles, buses, and some CHP applications. The PEMFC is potentially the most significant fuel cell being researched today. Industry has great hope for the PEMFC, some even sighting that it has surpassed all other electrical energy generating technologies in the breadth of scope and possible applications [2, 37].

The PEMFC gets its name from the solid-state exchange membrane that separates its electrodes. This membrane is just a hydrated solid that promotes the conduction of protons. Although many different types of membranes are used, by far that most common is Nafion, produced by DuPont. Other types of membranes being researched are; polymer-zeolite nanocomposite proton-exchange-membrane, sulfonated polyphosphazene-based membranes and phosphoric acid-doped poly(bisbenzoxazole) high temperature ion-conducting membrane [11]. As the Nafion membrane is so commonly used it is considered an industry standard, and all new membranes are compared to it.

The membrane allows for the transfer of protons and thus permits the general fuel cell process. At the anode Hydrogen separates into an electron and proton, freeing them to travel throughout the fuel cell. The electron travels externally in the circuit, while the proton travels through the conductive membrane to the cathode. The membrane must be hydrated for this to take place. The electron and proton then meet at the cathode where, in the presence of oxygen, water is formed. Since high temperatures are not necessary to hydrate the membrane, the PEMFC is one of the cooler running fuel cells operating at temperatures of 80°C or lower.

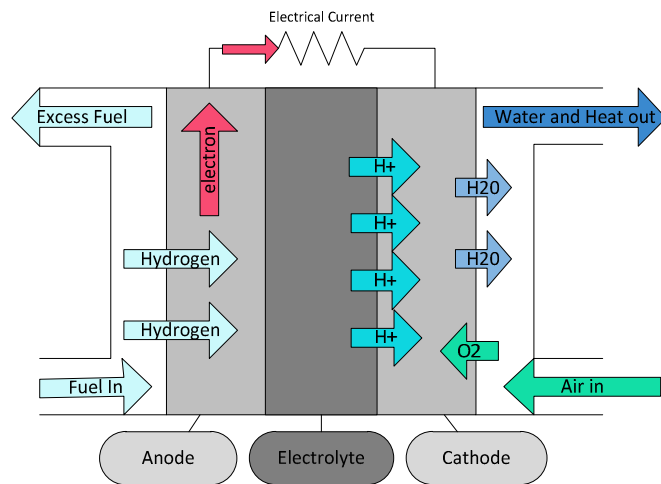


Figure 5-2 Structure and Flow of a PEMFC

The main concern in a PEMFC is management of water in the polymer electrolyte membrane. This concern arises as water is produced as a final product and it is important not to flood the electrolytes. Flooding of the electrodes causes a decrease in surface area, in which the separation of hydrogen or the formation of water takes place. The water cannot be simply removed since, as mentioned above, the membrane must remain hydrated; thus a balance must be achieved [38].

A further problem in water management is the susceptibility to have the air dry the water out at high temperatures. To solve this problem it is necessary to add water to the system to keep everything hydrated without over hydrating the cell. In order not to remove too much water from the cathode it is necessary to have the correct airflow.

$$Air\ Flow\ Rate_{cathode} = 3.57 \times 10^{-7} \times \lambda \times \frac{P_c}{V_c}$$

equation 5-1

Where λ is the stoichiometric ratio (in the case of the PEMFC $\lambda = 2$), P_c is the power of the cell in Watts and V_c , the voltage of the cell in volts.

The drying effect is highly non-linear with respect to the room temperature. The humidity ratio and relative humidity allow to qualitatively describe the necessary water conditions in the cell.

$$Humidity\ Ratio, \omega = \frac{m_w}{m_a}$$

equation 5-2

The mass of the water in the sample of the mixture, m_w is divided by the mass of the dry air m_a to give the humidity ratio.

$$Relative\ Humidity, \theta = \frac{P_w}{P_{sat}}$$

equation 5-3

Where P_w is the partial pressure of the water, and P_{sat} is the saturated vapour pressure.

The pressure relationship for the PEMFC is derived using the humidity ratio, relative humidity and the exit air flow rate equation. This equation establishes the vapour pressure at the exit, which is a function of the air properties and the operating pressure of the cell.

$$P_w = \frac{0.421}{\lambda + 0.188} P_t$$

equation 5-4

P_t is the operating pressure.

In order to complete the process the temperature must be incorporated which results in a decaying exponential. This graph is maximized in the region where the cathode will not be too dry or wet, typically $60^\circ C$, see Figure 5-3.

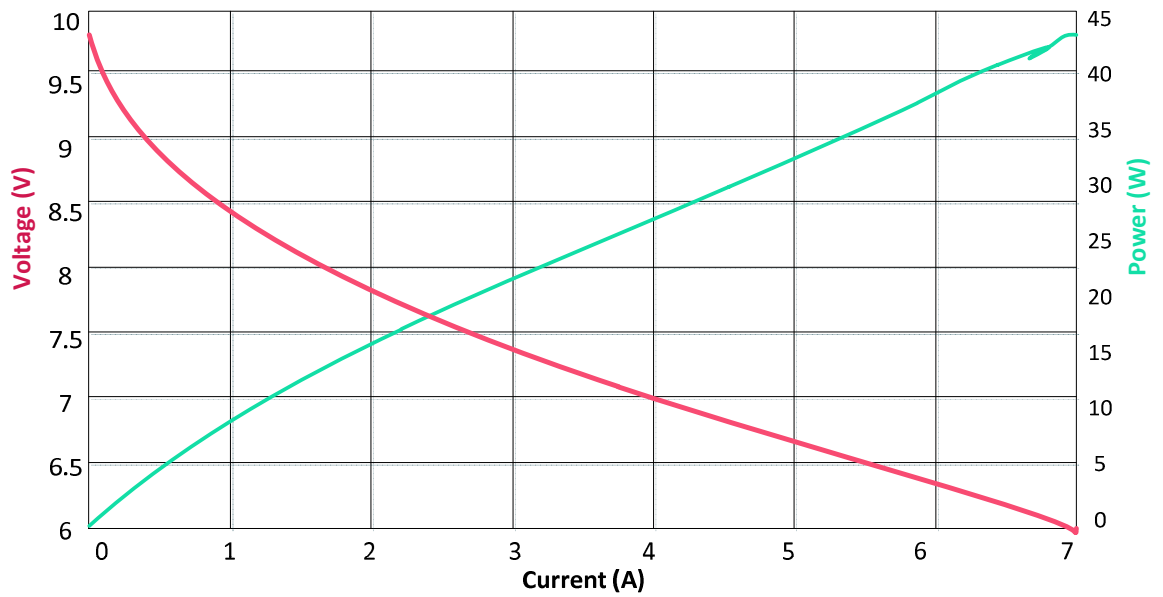


Figure 5-3 Temperature Dependence of the Cell

Pressurising the system could be beneficial, however this comes with certain costs; monetary, size, weight, etc. The major benefit is to supercharge the system, which gets a higher power rating out of a smaller device. A simple example of a pressurized fuel cell would be if a pressurized hydrogen container feeds it. In this case a motor would be powered by the fuel cell to compress the intake air, supplying an adequate amount of O₂ and satisfy water concerns.

The effects of pressure can be seen by modifying the equation for voltage equation 5-5 into a power equation 5-6.

$$\Delta E = \frac{RT}{2F} \ln \left(\frac{P_2}{P_1} \right)$$

equation 5-5

$$P_{gain} = C \ln \left(\frac{P_2}{P_1} \right) I n$$

equation 5-6

The power lost due to the need to compress the gases gives the total power loss equation 5-7

$$P_{lost} = c_p \frac{T_1}{\eta_m \eta_c} \left(\left(\frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) \dot{m}$$

equation 5-7

Here γ is the ratio of specific heat, m is the mass flow rate, η_m is the efficiency of the motor and η_c is the efficiency of the compressor.

By inserting known values and applying the definition of power we can solve for the total change in voltage.

$$\Delta E_{loss} = 3.58 \times 10^{-4} \times \frac{T_1}{\eta_m \eta_c} \left(\left(\frac{P_2}{P_1} \right)^{0.286} - 1 \right) \lambda$$

equation 5-8

The PEMFC is an ideal fuel cell to pursue for commercialisation. They can be operated at low temperatures which makes them a competitor to batteries. PEMFCS can also be scaled up for larger power applications such as passenger transportation. The cell can easily be stacked as their membrane is a solid-state material. The PEMFC offers a balance between power and size/operating temperature and will likely be the first cells commercialized on a large scale.

5.3 Direct Methanol Fuel Cells (DMFC)

Common Electrolyte	Operating Temp (°C)	Typical Power Output (kW)	Efficiency	Applications	Advantages	Disadvantages
Nafion	50-100	1-100	25 – 40%	- Mainly portable	- Ease of transport of methanol	- Low efficiency - Slow dynamic behaviour

Table 5-2 DMFC Summary Table

Pure hydrogen is not the only feedstock that can be used in fuel cells. A variety of reactions can produce hydrogen indirectly, thus enabling the classic hydrogen fuel cell chemical reaction to take place. Since methanol is a liquid at

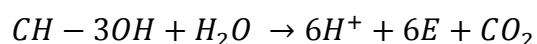
STP (boils at 65°C and 1atm) it can easily be stored and can be manufactured from a variety of carbon-based feedstock (such as natural gas, coal, and biomass- wood and landfill gas)



Figure 5-4 Potential Uses for DMFCs

The fuel cell system also has other design advantages over pure hydrogen fuel cells. They eliminate the fuel vaporiser and all the heat sources that are associated with it (methanol boils at low temperatures). They also remove the requirement for complex humidification and thermal management systems (again a consequence of the low operational temperature, and an on-board coolant in the form of the fuel itself). Finally, the size and weight of the overall system is substantially lower.

The operation of the whole DMFC system is similar to that of the PEMFC; however major difference is in the fuel cell supply. The fuel is a mixture of water and of methanol and it reacts directly at the anode according to the equation:



equation 5-9

The boiling point of methanol at atmospheric pressure is 65°C and therefore the cells require an operating temperature around 70°C. Much higher would give too high vapour pressure.

⁸ Photo from http://batteryuniversity.com/learn/article/the_miniature_fuel_cell

⁹ Photo from

<http://www.goauto.com.au/mellor/mellor.nsf/story2/07AD6E467C55A7A2CA25729800098951>

¹⁰ Photo from <http://www.mobilemag.com/2003/10/03/toshiba-announces-new-dmfc-fuel-cell-delayed-until-2005/>

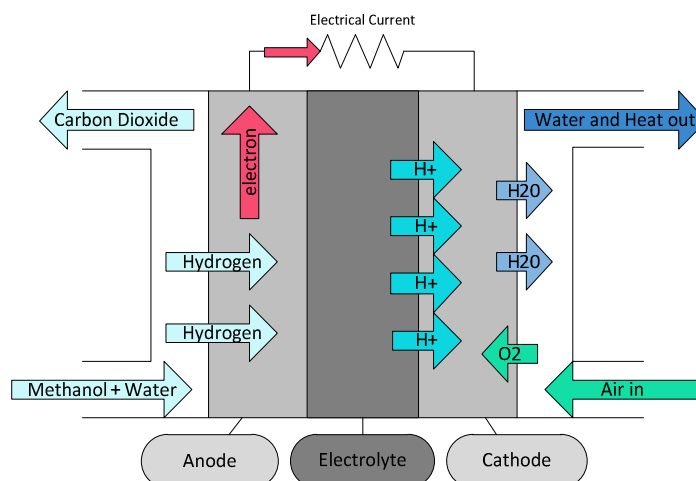
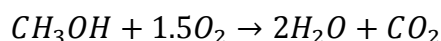


Figure 5-5 Structure and Flow of a Direct Methanol Fuel

The reaction mechanism is much more complex when considering reactions with the catalyst. This work will not cover DMFCs and as such will only review this fuel cell on basic equations. The total DMFC equation, representing only the initial and final products for both the cathode and anode is as follows:



equation 5-10

There are several issues that make the DMFC a less attractive option than the pure hydrogen fuel cell. These problems are mostly associated with the inability to get full potential out of the anode and the cathode. Acid electrolytes must be used because carbonate formation is problematic in an alkaline solution. There have been marked problems with the cathode and the anode having the same electro-catalysts. This results in a situation where it is possible to have "chemical short circuits" thus results in more inefficiency. The catalysts are typically high in platinum content making them highly susceptible to carbon monoxide poisoning.

These anode and cathode problems have made industry careful of the DMFC and as these listed problems have not been completely solved, yet DMFCs are not in full commercialisation.

5.4 Alkaline Fuel Cell

Common Electrolyte	Operating Temp (°C)	Typical Power Output (kW)	Efficiency	Applications	Advantages	Disadvantages
Aqueous solution of potassium hydroxide soaked in a matrix	50-100	10-100	60%	- Space - Military	- Cathode reaction faster in alkaline electrolyte leading to higher performance - Low cost components	- Sensitive to carbon dioxide in fuel and air - Electrolyte management

Table 5-3 Alkaline Fuel Cell Summary Table¹¹

In an alkaline fuel cell both the operating temperature and chemical reaction differ from that of other fuel cells. These fuel cells operate between 50 and 100°C.

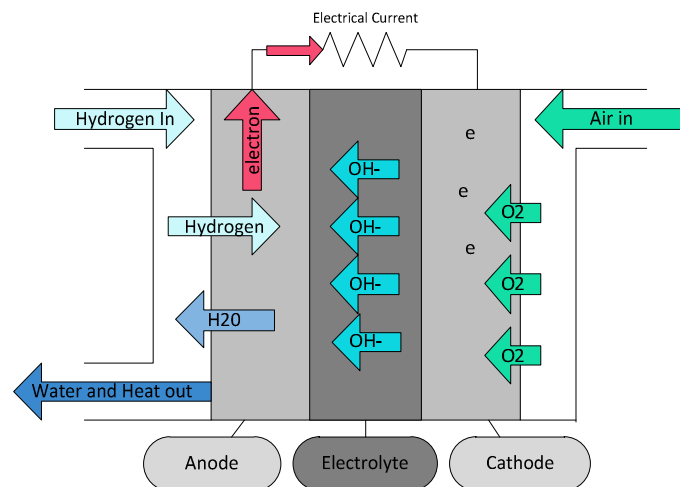
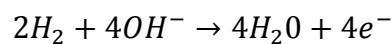


Figure 5-6 Structure of an Alkaline Fuel Cell

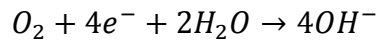
At the anode the following reaction takes place



equation 5-11

¹¹ Table from http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf

The electrons pass around the external circuit producing hydroxide ions at the cathode.



equation 5-12

The alkaline fuel cell was proven to be a viable source of power in the 1940s and was later used on the Apollo space shuttle taking the first men to the moon. They have been tested in a number of applications including tractors, cars, boats and offshore navigation equipment.

A disadvantage of the alkaline fuel cell is its slow reaction rate. Using highly porous electrodes with a platinum catalyst or operating the fuel cell at high pressures has overcome this. The air and fuel must be free of CO_2 to prevent poisoning of the catalyst. Other disadvantages include cost, reliability, ease of use, durability and safety.

Solving these problems has proven not to be cost effective compared to the number of other energy sources available during initial years of research. Additionally the success of PEMFCs drew development resources away from alkaline fuel cells. The main advances towards alkaline fuel cells still remains during the space program in the mid-1960s, in both the Apollo-series missions and on the Space Shuttle.

It is essential in this type of storage device to ensure no leaks because of the high flammability of pure hydrogen and oxygen. One solution is to encase the fuel cell inside a pressure vessel with an inert gas of higher pressure than that of the fuel cell. This ensures that any leaks do not escape the fuel cell, but instead the inert gas, such as nitrogen flows into the fuel cell instead [14].

An advantage of this type of fuel cell is that the activation over voltage at the cathode is usually less than in an acid electrolyte fuel cell. Additionally electrodes within alkaline fuel cells do not have to be made out of precious metals (although the use of platinum speeds up the reaction rate). Alkaline fuel cells can be categorized further by reviewing their pressure, temperature and electrode structure. These aspects vary widely between designs. One thing that rarely differs between alkaline fuel cells however is the use of potassium

hydroxide solution as the electrolyte. This fuel cell uses pure hydrogen as the fuel at the anode and air for the reaction at the cathode. To extract the water the hydrogen is circulated into a condenser. This is necessary as hydrogen evaporates the water produced. The fuel cell can be cooled using circulated hydrogen, which is an advantage of the mobile electrolyte. Another advantage is that by circulating the potassium hydroxide helps stop it from solidifying by preventing it from becoming saturated with water. Potassium hydroxide is slowly converted to potassium carbonate, reducing the efficiency and performance of the fuel cell. To prevent this problem a carbon dioxide scrubber is used to remove carbon dioxide from the air supply. It was for this reason the astronauts on the ill-fated Apollo 13 mission had to build carbon dioxide scrubbers to keep power supplied to the space shuttle. If the electrolyte reacts with carbon dioxide and becomes unusable this set up makes it a simple task to remove and replace the entire electrolyte. Alkaline electrolyte fuel cells generally operate at pressure and temperature much higher than the environment it operates in. The open circuit voltage of a fuel cell depends on the temperature and pressure and increases with increasing pressure and temperature. The actual increase in voltage is much higher. As the pressure increases this increases the exchange current density which in turn reduces the activation overvoltage on the cathode [2].

5.5 Phosphoric Acid Fuel Cell (PAFC)

Common Electrolyte	Operating Temp (°C)	Typical Power Output (kW)	Efficiency	Applications	Advantages	Disadvantages
Phosphoric acid soaked in a matrix	150-200	100-400	40%	- Distributed generation	- Higher temperature enables CHP - Increased tolerance to fuel impurities	- Pt catalyst - Long start up time - Low current and power

Table 5-4 Phosphoric Acid Fuel Cell Summary Table¹²

¹² Table from
http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf

The electrode material is generally platinum and the electrolyte is concentrated phosphoric acid, hence the name of the fuel cell. Phosphoric acid is used as the electrolyte because it is the only inorganic acid that exhibits the required thermal stability, chemical and electrochemical stability and low enough volatility to be effectively used [2]. Carbonate formation is not a problem with phosphoric acid fuel cells as Phosphoric acid does not react with CO_2 such as the case with alkaline fuel cells. Phosphoric acid has a freezing point of 42°C , which is high compared to electrolyte materials used in other fuel cells. If the electrolyte is allowed to freeze it will expand, causing internal stresses in the system. For this reason the fuel cell electrolyte is kept at a temperature above 42°C .

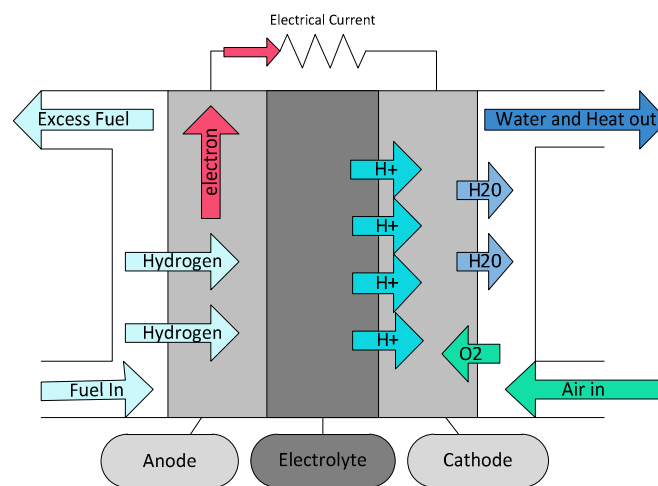


Figure 5-7 Structure of a Phosphoric Acid Fuel Cell

The matrix holding the electrolyte is made from silicon carbide with particles approximately 1 micron in size. This thickness allows considerably low ohmic losses and the structural matrix is thick enough to prevent crossover of the reactant gasses from the anode to the cathode. Phosphoric acid fuel cells were the first commercially available fuel cells. Many PAFCs have operated for years upon which much knowledge and technological improvements have been made. The quality of the power produced and the reliability of the stack have been greatly improved. Unfortunately the cost of technology is still too high to be economically competitive with alternative power generation systems. Research is being directed to increase the power density of the cells and reduce costs which both affect each other.

5.6 Solid Oxide Fuel Cell (SOFC)

Common Electrolyte	Operating Temp (°C)	Typical Power Output (kW)	Efficiency	Applications	Advantages	Disadvantages
Yttria stabilized zirconia	700-1000	1-1000	60%	<ul style="list-style-type: none">- Auxiliary power- Electric utility- Distributed generation	<ul style="list-style-type: none">- High efficiency- Fuel flexibility- Can use a variety of catalysts- Solid electrolyte- Suitable for CHP	<ul style="list-style-type: none">- High temp corrosion and breakdown of cell components- Long start up times

Table 5-5 Solid Oxide Fuel Cell Summary Table¹³

SOFCs are made up of cylindrical layers, three of which are made from ceramics. The cells are much smaller than those in other types of fuel cells and as such hundreds are connected together to create a SOFC stack. SOFCs run at very high temperatures, typically 500 to 1000°C, as this is when the ceramics used become electrically active. Similarly to other fuel cells, the current is produced by the reduction of oxygen at the cathode. Two electrons are released and travel through the external circuit.

The fuel flows towards the electrolyte through the ceramic anode layer and as such this must be very porous and conduct electrons. The most common material used is a mixture of ceramic and nickel, typically a zirconium-based ceramic called yttria stabilized zirconia (YSZ), which prevents the nickel grains from growing.

¹³ Table from
http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf

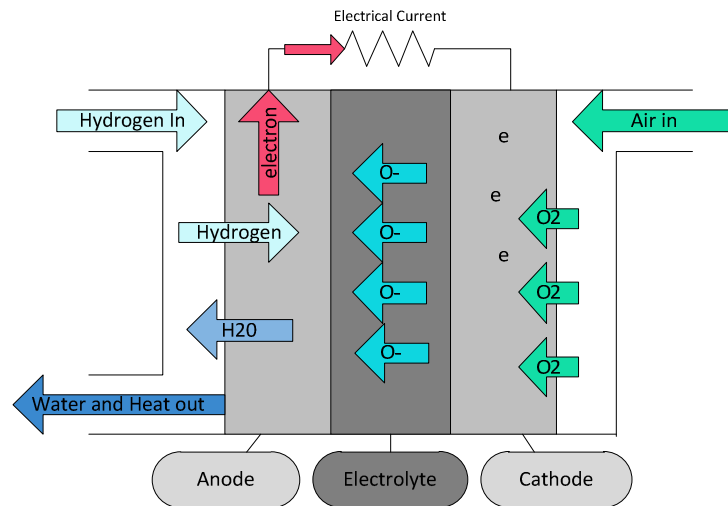


Figure 5-8 Structure of a Solid Oxide Fuel Cell

The anode is typically the thickest and strongest layer in the cell. It is this layer that gives the mechanical support to the cell. The anode can also be used as a catalyst for steam reforming the fuel (for example light hydrogen such as methane) into hydrogen. This reaction is endothermic which cools the stack internally. A dense layer of ceramic forms the electrolyte, which conducts the oxygen ions. The electronic conductivity of this layer must be kept to a minimum to prevent leakage current losses. As the temperature of the SOFC increases the losses reduce. The cathode is where the oxygen reduction takes place and is a thin porous layer. The thermal expansion of all materials used in a SOFC must be well matched otherwise there would be significant movement of the material on start up as material expands as the temperature increases [17].

Research is currently underway by Delphi Automotive Systems, BMW and Rolls-Royce into future applications of SOFCs. These include SOFCs to power the auxiliaries on automobiles and tractor trailers as a high temperature SOFC could provide enough power to generate all the electricity required, resulting in hybrid vehicle with a smaller and more efficient engine [39].

5.7 Molten Carbonate Fuel Cell (MCFC)

Common Electrolyte	Operating Temp (°C)	Typical Power Output (kW)	Efficiency	Applications	Advantages	Disadvantages
Solution of lithium, sodium and/or potassium carbonates soaked in a matrix	600-700	300-3000	45-50%	<ul style="list-style-type: none"> - Electric utility - Distribute generation 	<ul style="list-style-type: none"> - High efficiency - Fuel flexibility - Can use a variety of catalysts - Suitable for CHP 	<ul style="list-style-type: none"> - High temp corrosion and breakdown of cell components - Long start up times - Low power density

Table 5-6 Molten Carbonate Fuel Cell Summary Table¹⁴

MCFCs operate at 600°C and above using an electrolyte of a molten carbonate salt mixture suspended in a porous, chemically inert, ceramic matrix. The high operating temperature means non precious metals can be used as a catalyst making the cost come down. The MCFC is also a more efficient fuel cell when compared to the PAFCs, approaching 60% without reclaiming lost heat and up to 85% with heat recovery in place [40].

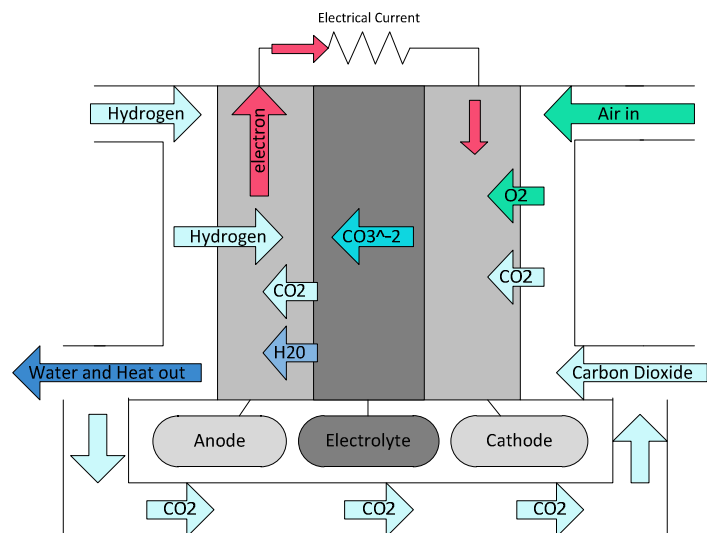


Figure 5-9 Structure of a Molten Carbonate Fuel Cell

¹⁴ Table from http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/pdfs/fc_comparison_chart.pdf

Carbon monoxide does not damage MCFCs and can use fuel made from coal without the concern of poisoning the fuel cell. They are more resistant to impurities than other fuel cells and with further research could be capable of internal reforming of coal. MCFCs don't require an external reformer as the high operating temperature allows the fuel cell to internally reform hydrogen from energy dense fuels.

6.1 Introduction

Fuel cells are excellent energy sources when providing power to steady state loads. In general, fuel cell systems feed hydrogen and oxygen into the fuel cell membrane that generates a voltage across the membrane. A load connected to the membrane provides current flow. Changes in the load result in a change in the current. In order to provide the same power across the load, the fuel cell membrane needs to provide more or less voltage. With the purpose of changing the generated voltage, the flow rate of hydrogen and oxygen must be changed (commonly this is controlled by electro-mechanical valves) [41]. It is well known that valves have slow response times and for that reason fuel cell systems are prone to highly dynamic load changes. In addition fuel cell membranes have slow electrochemical and thermodynamic processes that add to the slow valve response time causing delays in the voltage build-up or voltage reduction across the membrane. For that reason fuel cell systems are not suitable for highly dynamic load changes and any applications that experience these load changes must be carefully investigated. FC vehicles are an application where the fuel cell must deal with random load changes e.g. accelerating and braking a vehicle will cause different load response.

It is therefore of paramount importance to evaluate the right fuel cell system for a given application. In order to receive meaningful data this process requires simulation software. The backbone of simulation software packages is the models that are implemented in the software. This chapter provides a generic overview of simulation software and the models used to represent fuel cell systems. Off-line models are used in simulations, which are not linked to any high voltage hardware, and normally this kind of simulation is carried out away from the FC vehicle [42]. On-line models are implemented in software that is running in real-time and the coding is embedded in a high voltage high current hardware that emulates a fuel cell. This emulator is commonly connected to the vehicle [43-56].

A fuel cell system can also be modeled in an electrical equivalent circuit model [57, 58]. The fuel cell behaviour is formulated using a set of governing equations; these enable the fuel cell to emulate its real-life performance in terms of operating conditions. This method of fuel cell modeling forecasts the voltage–current characteristics of the fuel cell operation by using parametrical equations and related parameters. The model examines all the physical and chemical reactions within the fuel cell without going into too great detail. Different components and forms of energy generated are included within the model. In order to obtain accurate simulation results model parameters must be precisely identified. Model validation is achieved by comparing simulated and experimental results. The strong alignment between the experimental results and results produced by the model, shows that a model can provide an accurate representation of the static and dynamic behaviour for the PEMFC. Therefore, their approach allows the user to evaluate the set of parameters within analytical formulation of any fuel cell [59].

Fuel cell models assist a better understanding of what parameters affect a fuel cells performance. In order to achieve simulation results that are close to the real behaviour of a FC system models must be of highest accuracy [60]. However, highly accurate models may not always be feasible to have as they may take too long to develop and increase processing time leading to long simulation times. It is therefore important to clarify the key features that are required from the model before selecting or developing a model. This initial criterion often tends to be overlooked. .

6.2 Model Parameters and Selection

A clear definition of the models objective is essential, as both technical and organisational restraints will affect the outcome. Organizational resources, in terms of personnel, cost and time, can be taken into account but will not be covered within this thesis. The technical constraints include the intended application of the model, the required level of details, the technical capability of the end user and information available on the fuel cell to be modeled, need to be clarified in order to make the best choice of fuel cell model [61]. The development process can be costly and time consuming. The design of a new

FC model is often unnecessary as validated and reliable commercial fuel cell software is readily available with defined models that may be an appropriate solution. Commercially available software may also include 'ready-to-use' fuel cell models. These often have the potential for user-defined modifications or a library of components for construction of a customer-defined model. At first glance these would appear to be time-saving; however, proper evaluation of available commercial software can be time consuming depending on the software complexity. Although software usually comes with developer support, the time required for training and model modifications needs to be accounted for [62].

In the end the optimal choice will differ for each end user application but correct selection is essential, as changing the model later will be costly in both time and money. Once the initial application has been set more detailed evaluation of the model can take place, considering the content and structure.

There are numerous models currently available modeling proton exchange membrane (PEMFC) fuel cells and fuel cell systems. Each model puts emphasis on different features and uses a different approach to model the fuel cell. The most common key features are as follows; whether the model is theoretical or analytical, steady state or transient, where the system boundary is defined, the spatial dimension of the model, the model complexity and how it has been validated [62]. The key features provide a good base to choose the models to consider for a real-time virtual fuel cell.

As the aim of this chosen model is for it to be run in real-time alongside the other auxiliary systems in the VFCS, one of the key points to be noted is the complexity of the model. If the model chosen were to be too complex then the processing power needed to run the final system would be too great to be cost effective [63].

6.2.1 Theoretical



A theoretical or mechanistic fuel cell model is based on electrochemical, thermodynamic and fluid dynamic relationships. Examples of these include the Nernst-Planck equation for species transport, the Stefan-Maxwell equation for gas-phase transport and the Butler-Volmer equation for cell voltage [12].

Models may provide output detailing behaviour of the fuel cell stack such as cell flow pattern, current density distribution, voltage and pressure drops. This level of detail may be too in depth for the intent of the model. These models take a substantial amount of time to develop and validation can be difficult to achieve.

Semi-empirical fuel cell models are based on experimental data specific to each application and operating condition. They are not as in-depth as theoretical models as they draw from results demonstrating behaviours of previously analysed models. They are validated using the experimental data and provide a fast start into fuel cell engineering applications. Semi-empirical models are adapted for a specific application and therefore must be modified for new operating conditions or applications. The boundary between a theoretical and semi-empirical model is not that clear cut. A fuel cell system model could use a theoretical model of the fuel cell and empirical maps of compressors and other devices in the system [64].

6.2.2 The state of the model

Models are designed to describe steady-state, transient or quasi-steady-state responses. The state of the model may also be related to the system boundary. The state of the model chosen relies heavily on the simulation objective, e.g. stationery or transportation fuel cell applications. Steady-state models are useful for sizing system components, calculating amounts of materials such as catalysts and evaluating changes in parameters within the model. Fuel cells are operated in steady-state in laboratory environments. When variations to the load are plied fuel cells respond immediately, however when integrated into the fuel cell system this increases the response time. For use in a vehicle a dynamic model accounts for the important transients particularly apparent in a

vehicular fuel cell system. If the efficiency of the fuel cell is calculated at steady-state it would only give part of the picture. Transient models are most useful for start-up and shutdown procedures. Here they can be used to analyse influences of the components in the system on the flows during the drive cycle. It can also be used to optimise the response time on a varying load.

6.2.3 System boundary

The system boundary defines the physical area the model will represent. This ranges from the fundamental cell level including electrodes and the membrane. A higher level model may represent individual fuel cells assembled in fuel stack. A virtual fuel cell system will go one step further including a fuel cell stack with its auxiliary components. These include a compressor, pumps and so forth.

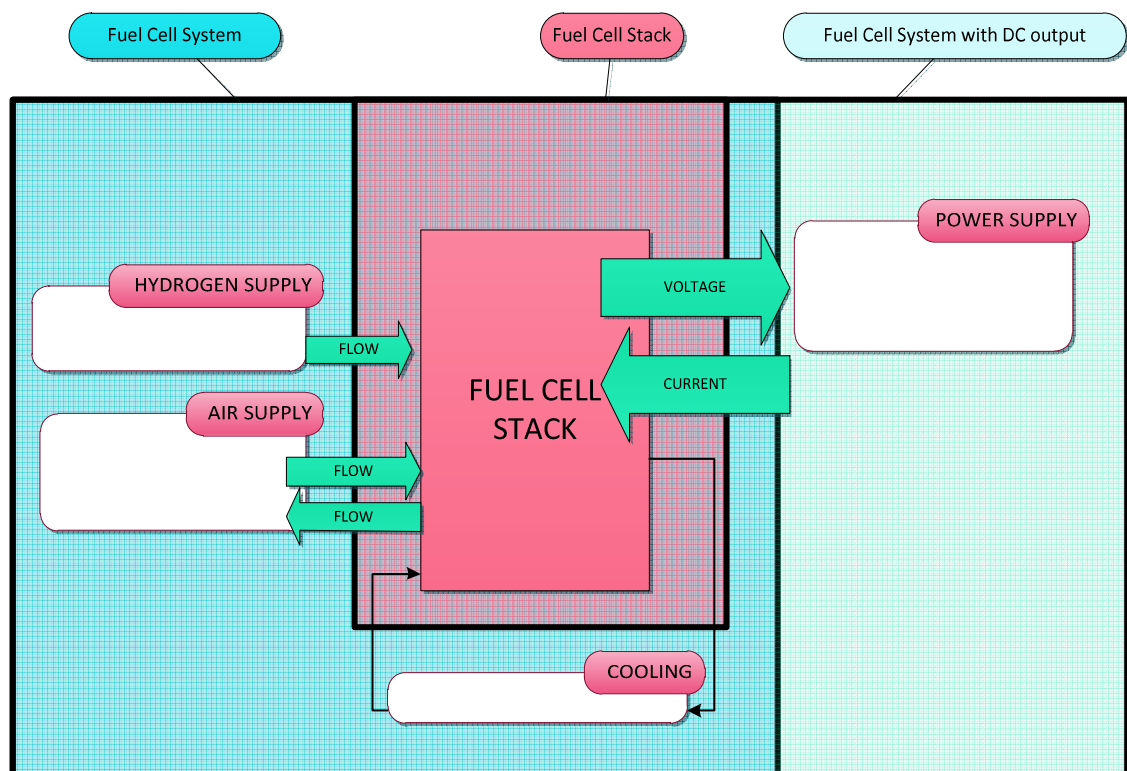


Figure 6-1 Fuel Cell System

6.2.4 Spatial dimension

For fuel cell systems, zero dimensional models are sufficient. A 0 dimension model contains no equations with spatial dimensions [62]. The equations describe scalar variables such as the cell voltage but cannot predict spatial distribution of physical quantities e.g. the temperature distribution in individual cells. This kind of model is often used to describe the fuel cell polarisation

curve. The description of the fuel cell, taking into account phenomena such as mass transport limitation, requires at least one dimension. Three dimensional models are the most comprehensive fuel cell model. They contain detailed exploration of detailed phenomena and as such the complexity and computation time is comparatively high [65].

6.2.5 Complexity

The complexity of the model can be controlled by limiting what phenomena is calculated and what can be assumed to remain constant. As the complexity of the model is increased, a more accurate representation of the fuel cell is achieved. A detailed picture of all processes in the fuel cell and the fuel cell system can be achieved by including heat transfer equations and mass and energy balances. If thermal and water management is to be included, the model should contain thermodynamic and fluid dynamic equations as well as electrochemical relationships [66-68]. As with all key features there is a compromise to be made between model accuracy and processor computing time and cost.

6.2.6 Source code

Software providing various system component blocks to choose from can provide a good benchmark test for a fuel cell model. Model input specifications can be complex or use inflexible code [62]. This makes it difficult to use or amend code for a specific application. In order to fully understand and use the model the user must know the algorithms and where simplifications been applied. An ideal model would have an open source code with no masked subsystems. A greater understanding of the model is often attained by a well-written manual and tutorial, and hands-on support from the software developer.

6.2.7 Validation

A model must have some validation to be regarded as a credible tool and appropriate data is needed for this validation. Master data cannot be found in open literature so this can be difficult. Data from the complete fuel cell system is also difficult to obtain without a system to take results directly from. It is easier

to acquire data from single fuel cell system components, for example the stack or compressor. It is recommended in literature that the best way to deal with lack of data is to develop well-defined subsystem models and validate them separately [8]. This can then be assembled for implementation in a larger model. Well defined models can be more accurate than the corresponding measurement so this must also be taken into account when validating.

6.3 Theoretical Fuel Cell Models Constructed from Literature

A large variety of PEMFC models have been described in the open literature over the last decade. These range from simple zero dimensional fuel cells to a range of complex three-dimensional models. These models take different modeling approaches and go into varying levels of detail. As the aim of each model is different, they vary in level of detail and complexity. Most models account for phenomena in fuel cells using a theoretical approach. It is difficult to find a good overall FCS model as each model normally focuses on one aspect or region of the fuel cell only. This means FCS's can only be achieved by the end user assembling an FC system from the components presented in these models.

Semi-empirical models provide a general voltage current relationship. However these relationships have no physical justification and are specific to one particular FC stack. Each new cell configuration requires recalculation of the coefficients in the voltage current equation. This means this type of model is limited as predictive tool. Most fuel cell models use a simplified approach in the electrochemical aspects e.g. electro kinetics and mass transport limitation. Models are generally semi empirical. Additional thermodynamic and fluid dynamic relationships are added for the auxiliary system.

6.4 Commercial Fuel Cell Models

Ready to use models are attractive options when time is limited as constructing and validating models from literature is time-consuming. Commercial fuel cell models are readily available alongside additional software modules. This means

fuel cell systems are relatively easy to construct [69]. Examples of fuel cell models include COMSOL: Simulation Software – Batteries and Fuel Cells Module, AVL Fire (3D CFD simulation), GCTool, Argonne National Laboratory (ANL) and MATLAB SIMULINK.

The simulation purpose and constraints such as time and cost have a great influence on the choice of whether develop to develop a proprietary fuel cell model or acquire ready to use software. From these commercially available fuel cell models, and theoretical models available in literature, three were chosen to evaluate in greater detail for use in the virtual fuel cell system.

6.5 Real – Time Simulation

Simulation tools have progressed over time in line with the advancement of computing technologies. Researchers and engineers now have access to high performance, affordable tools which were previously only affordable to large manufacturers [45, 46, 70-79].

Real-time simulations use discrete-time steps where time is recorded in steps of equal durations. This fixed time-step simulation is best suited for real-time simulations as variable time steps, which can be used for solving nonlinear systems and high frequency dynamics, can be complex to process in real-time [74].

When solving equations within the given time step each variable must be solved successively “as a function of variables and states at the end of the preceding time-step” [74]. During offline simulation the time required to compute the equations can be shorter or longer than the duration of the simulation time-step. It does not affect the outcome of the simulation as to when the results of each function are available in the model. See Figure 6-2 part (a) and (b).

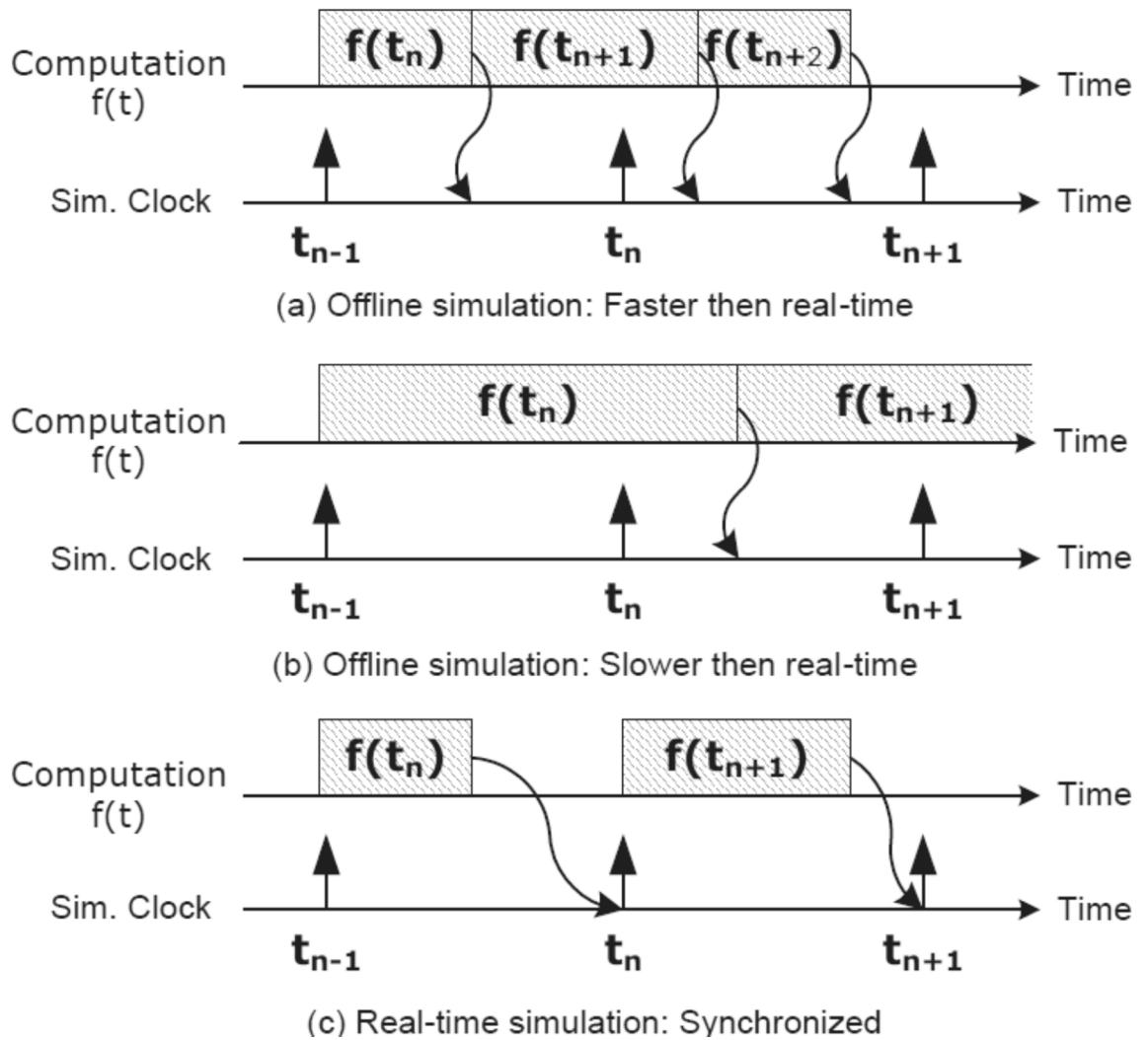


Figure 6-2 Offline simulation (a) and (b) alongside Real-time simulation (c)¹⁵

Real-time simulation requires the simulator to accurately calculate the internal variables and outputs of the simulation within the same length of time that it would in a physical system. This principle is demonstrated in Figure 6-2 (c). In real-time simulation the accuracy of the results depends on the length of time to produce the results alongside the precise dynamic representation of the system. The time required to calculate the function must be shorter than the time-step of the system. The remaining time before the next calculation is lost as idle time. If the operations are not complete within this time however it is known as “overrun” and results in an inaccurate model. Within each time-step the simulator performs the same sequence of operations see Figure 6-3.

¹⁵ “The What, Where and Why of Real-Time Simulation” J Belanger Member IEEE

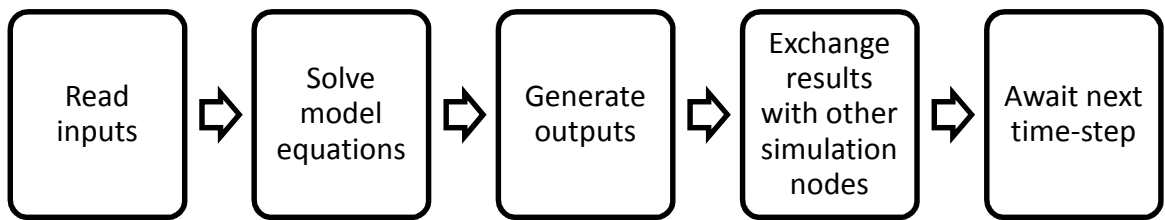


Figure 6-3 Real-time simulation process steps

The size and cost of real-time simulators are determined by multiple criteria. The first being the frequency of the highest transients to be simulated (this influences the minimum time-step which can be used in the system). The second is the intricacy or the size of the system to be simulated. The typical time-step and computing power requirements can be seen in Figure 6-4.

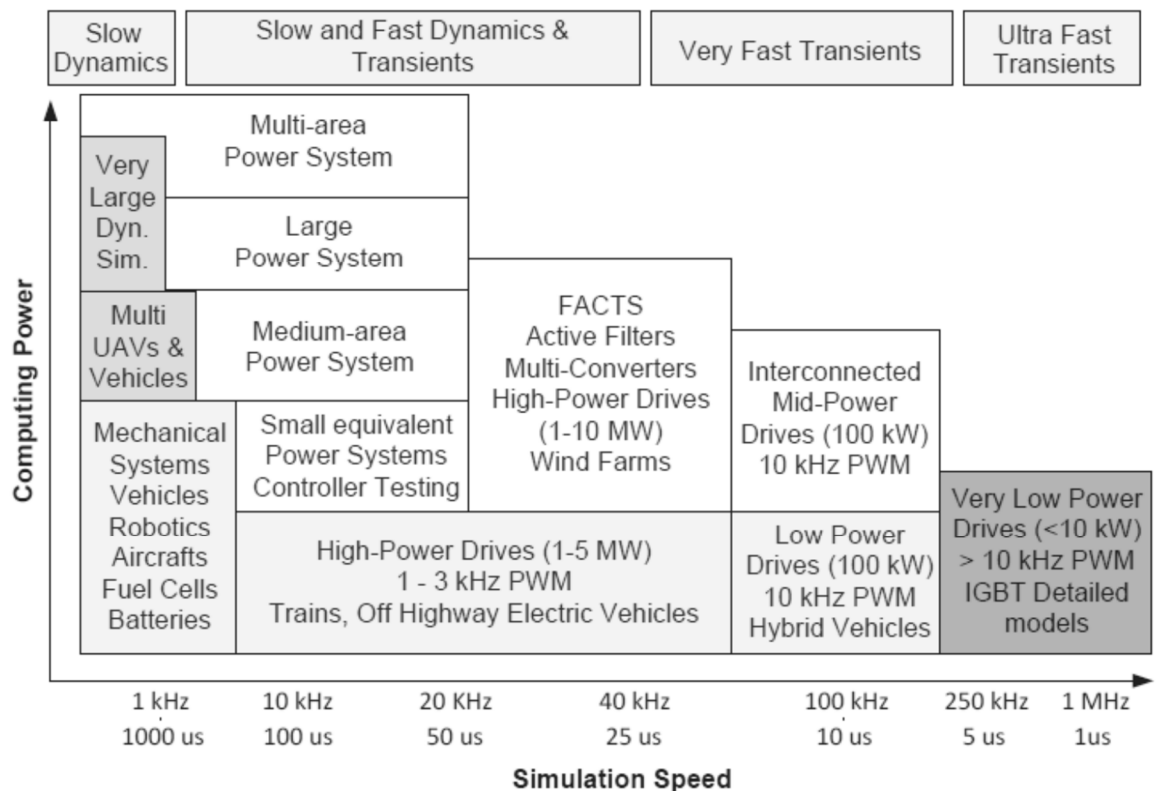


Figure 6-4 Simulation time-step by application¹⁶

¹⁶ "The What, Where and Why of Real-Time Simulation" J Belanger Member IEEE

7.1 Introduction

Multiple models were considered for use within the VFCS. The shortlisted were as follows; Mathworks Simulink FC block, Spiegel MATLAB PEMFC model [80] and Nehrir PEMFC model [15]. Each of these models was chosen as they represent characteristics common to the large number of FC models currently available and therefore allows multiple modeling approaches to be analyzed.

7.2 Matlab Simulink Model

7.2.1 Overview

The first model considered (Mathworks model) uses Simulink and is a theoretical model with a proprietary source code. Two models are available within Simulink; a simple model and a detailed model. Initially the Mathworks model was favoured as it had been created directly for Simulink, however it proved the most difficult to validate due to masking and restricted user access to key inputs.

7.2.2 Mathworks – Simplified Model

The simplified model is based on an equivalent circuit. The user can change the parameter data based on specific fuel cells (assuming the data sheet for that fuel cell is readily available). This however, just changes the Tafel slope see Figure 7-1 and subsequently this model has been ruled out due to its over simplicity. Although the limited inputs would allow it to be easily integrated into industry, it limits the possibilities of testing “what if” scenarios.

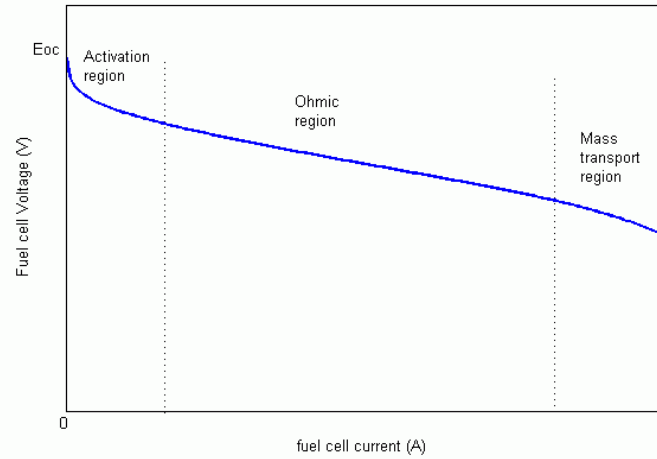
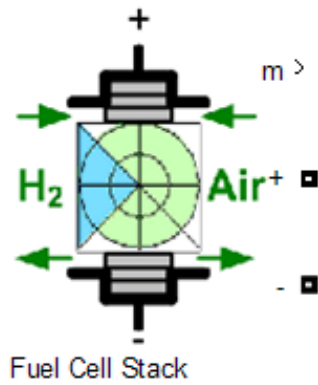


Figure 7-1 The Simulink FC block and simplified Tafel slope

7.2.3 Mathworks – Detailed model

The detailed Mathworks model is much more complex. It includes electrochemical, thermodynamic and fluid dynamic relationships. Although this model goes in to sufficient detail regarding the reactions taking place from within the fuel cell, this model was ruled out due to accessibility of these equations. The model contains masking between levels and as such cannot be modified. Information regarding validation of this model is also unavailable.

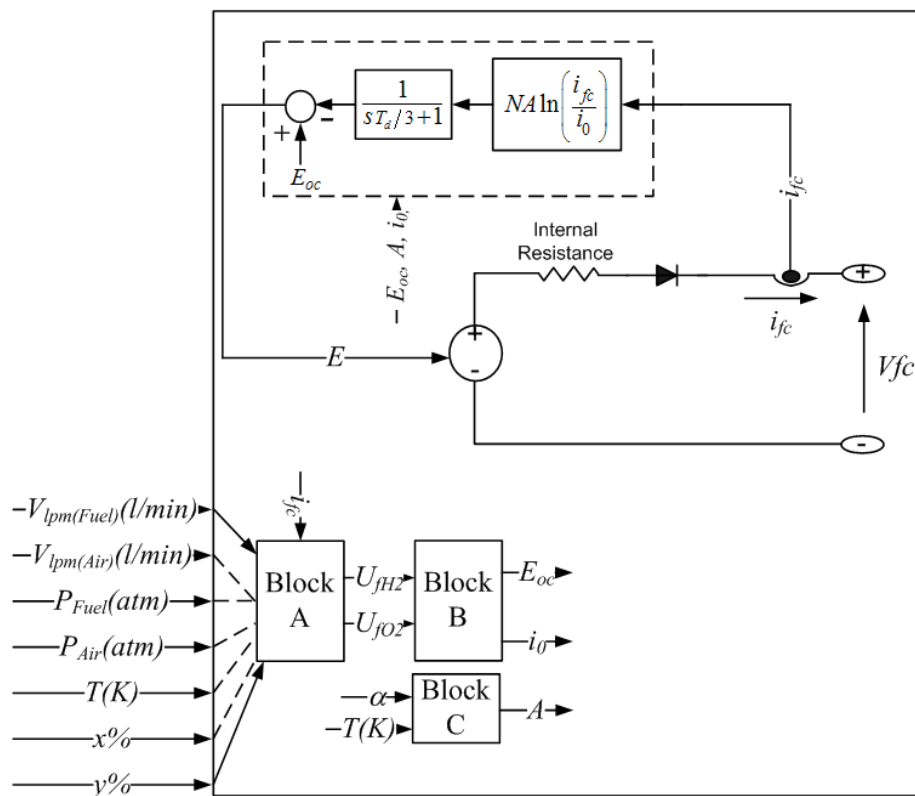


Figure 7-2 Mathworks detailed FC model

7.2.4 Conclusion

There are many distinct advantages in using an established commercial fuel cell model however this model was ruled out as it would not allow any future modifications needed to investigate various failure scenarios or the integration of auxiliary components [81].

7.3 Coleen Spiegel Model

7.3.1 Overview

This model, produced by Colleen Spiegel, has been built within MATLAB. This model is entirely theoretical. The model goes into great depth on the chemical reactions taking place within the fuel cell [80]. The model uses fundamental equations representing the behavior of fuel cell to generate the code within MATLAB. Over twenty parameters have been identified which must be solved or inputted into a mathematical model of a fuel cell, which can be seen in Table 7-1. This model would require a large amount of computing power in order to solve for each of these parameters and run in real-time.

Hydrogen Properties	Oxygen Properties	Water Properties	Material Properties
P : pressure	P : pressure	P : pressure	T : temperature
X_H2 : mole fraction	T_O2 : temperature	T_H2O : temperature	K : electrical or ionic conductivity
T_H2 : temperature	X_O2 : mole fraction of oxygen	X_H2O(l) : mole fraction of liquid water	K : thermal conductivity
X_H2O(l) : mole fraction of liquid water	U : velocity	X_H2O(v) : mole fraction of water vapour	E : void fraction
X_H2O(v) : mole fraction of water vapour	M : molar flow rate	U : velocity	Rho : density
U : velocity		M : molar flow rate	A : area
M : molar flow rate			T : thickness

Table 7-1 Spiegel key parameters[80]

The model can be used to assess both Steady State and Transient behavior. A model used in a vehicle should be dynamic allowing it to account for the fundamental transients in the system. If the efficiency of this system were to be calculated at steady state it would not give the full picture. For start-up and shut down procedures transient models are used. Transient models are also used to

analyze how each component can affect the flow whilst the fuel cell is in operation and optimize the response time when there are changes in the load [62].

The Spiegel model covers both the thermal and water management needed within the FC. The model contains the electrochemical, thermodynamic and fluid dynamic equations. The heat transfer equations and mass and energy balances show all processes within the fuel cell to great detail. Although commenting within her work that the more realistic method of modeling would use complex multistep reaction kinetics for the electrochemical reactions, this model focuses on Butler-Volmer type expressions to model the reactions taking place at the electrode [12].

7.3.2 Conclusion

The Spiegel model would require the user to input excessive detail about the FC which is to be modeled. It is all encompassing with the reactions considered and modeled. There are few assumptions made and all reactions are calculated. The model provides a useful tool to understanding the processes within the fuel cell, but would require substantial computing power to run in real-time. Subsequently this model has been ruled out [81].

7.4 Nehrir

7.4.1 Overview

This final model uses a semi-empirical approach and is operated in Simulink [15]. The model contains look up tables for the current values for steady state (ideal), steady state (real) and transient flows. It draws from look up tables to plot the voltage and power output generated within the model. This model allows the user ability to replace the look up tables with data for different fuel cells or load profiles.

The Nehrir dynamic model has been developed for PEMFC based on physical principals. Analytical expressions were derived from the following

- The PEMFC equivalent internal voltage source.
- The activation, ohmic and concentration voltage drops.
- The activation, ohmic and concentration equivalent resistance.

The Simulink model for calculating the voltage output and losses is shown in Figure 7-3

The system boundary ends at the fuel cell. Additional auxiliary components can be integrated into the model to produce a complete VFCS. Nehrir's FC model has been built to run at a fixed time-step. Additional testing has been performed within dSpace and the model has also shown promising results when operating in real-time.

This model was originally validated against a 500W SR-12 PEMFC stack from Avista Labs. The changes to the outputs in the models responses are as expected within the FC. The model also shows an error of approximately 1% when predicting the temperature of the FC. This figure is only correct as long as there are no external influences on the FC such as cooling fans, which would be present in an automotive fuel cell system.

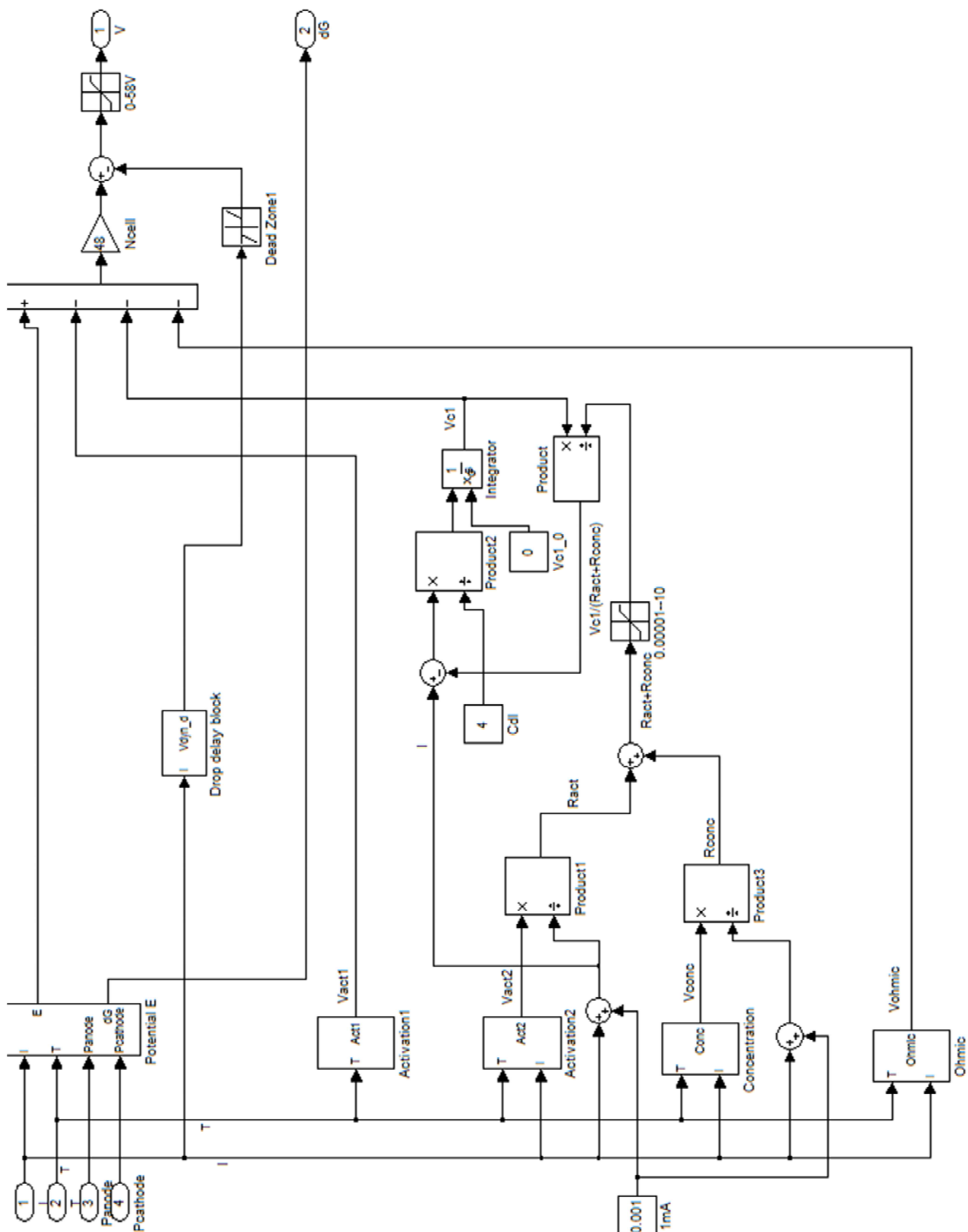


Figure 7-3 Voltage and voltage loss calculation within the Nehrir Simulink model for PEMFCs

7.4.2 Conclusion

The FC models developed by Nehrir are openly available. The models can be manipulated to fit within any desired system. There is no masking in place so it is easy to track the equations through the different layers of the model. The Nehrir model is semi-empirical. It uses look up tables for the current; steady-state ideal, steady state real and transient. There is an opportunity to replace these lookup tables with another if that would be more suitable for the virtual fuel cell system.

This fuel cell model does not take into account the effects of the auxiliaries on the system and the system boundary only looks at the fuel cell stack. It would be relatively easy to integrate additional components into the model.

Chapter 8. Auxiliary system modeling

8.1 Introduction

As discussed in previous chapters there are many fuel cell models currently available, each with their own strengths and weaknesses. The focus of each model differs with the design intent; some models focus on transient effects whilst others group parameters into differential equations (as the effects on the performance are negligible). For a PEMFC sized for automotive propulsion the relevant time constant can be seen below [8].

Component	Order of Magnitude
Electrochemistry	10-19 sec
Hydrogen and Air Manifolds	10-1 sec
Membrane Water Content	(unclear)
Flow Control/Supercharging Devices	100 sec
Vehicle Inertia Dynamics	101 sec
Cell and Stack Temperature	102 sec

Table 8-1 Time Constants for and Automotive PEMFC

This shows that the transient phenomena of both electrochemical reactions and electrode dynamics are extremely fast and therefore can be ignored. These will have minimal effects in automotive application. However what cannot be ignored are the transient behaviors resulting from the manifold filling dynamics, membrane water content, supercharging devices and temperature as these will have an effect on the vehicles behavior [82-86]. The virtual fuel cell model produced in this thesis does not contain a supercharger and as such this element will not be discussed further.

The subsystems in a fuel cell system are fairly standard and can be seen in the next diagram.

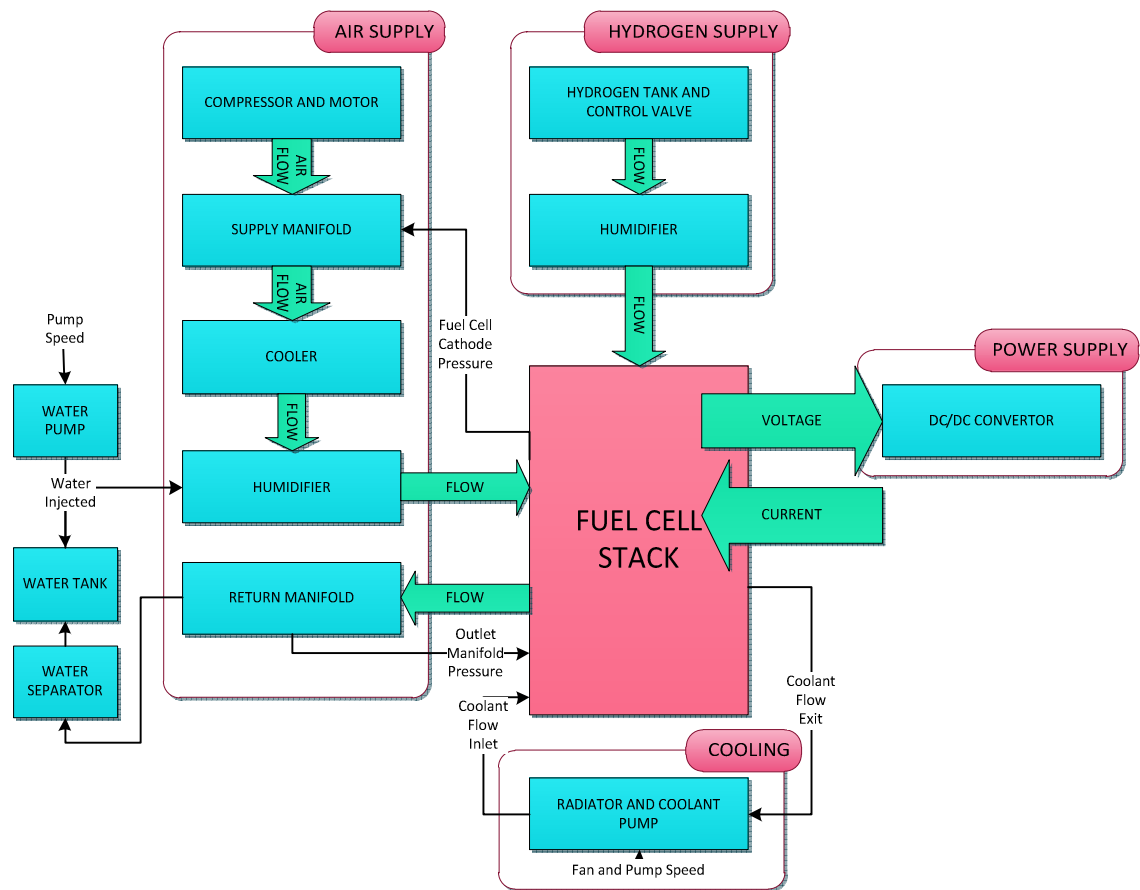


Figure 8-1 Fuel Cell System

In order for a fuel cell system to be viable, efficient and robust, precise control of the reactant flow, pressure, temperature and membrane humidity is critical. The resulting task is complex because of the interactions and conflicting objectives of each component. To simplify this, the overall system could be split into four subsystems. Each system has a corresponding objective and interactions with other subsystems. The subsystems are as follows

- Air Supply
- Hydrogen Supply
- Cooling
- DC-DC Converter (this is not part of the model; instead it could be included at a later date as a physical piece of equipment in order to run the VFCS in the place of a fuel cell).

The auxiliaries for the virtual fuel cell were based on the work of Jay T Pukrushpan who has published many papers on modeling auxiliary components of PEMFC systems for automotive applications. The reactant flow subsystem consists of hydrogen supply and air supply loops [8]. The airflow in the cathode and the hydrogen flow in the anode are adjusted using the compressor and valve commands. This reflects the FC vehicle motor as it draws current and subsequently the hydrogen and oxygen levels in the fuel cell stack become depleted. The control ensures there is sufficient reactant flow to minimize the auxiliary power consumption and ensure a fast transient response. It is difficult to avoid a slow response in the system and work has been done to overcome this by building a forward feed map and tuning this to different ambient conditions. Some experimental systems use a fixed speed motor to satisfy the maximum traction requirements however this can lead to unnecessary auxiliary power consumption during low load operations.

8.2 Air Supply System

The air supply system is one of the most important auxiliary components in a fuel cell system and a lot of research has been carried out in optimizing these [87-96]. In a PEMFC the air supply system typically consists of a compressor, a humidification device and a pressure control valve.

8.2.1 The Compressor

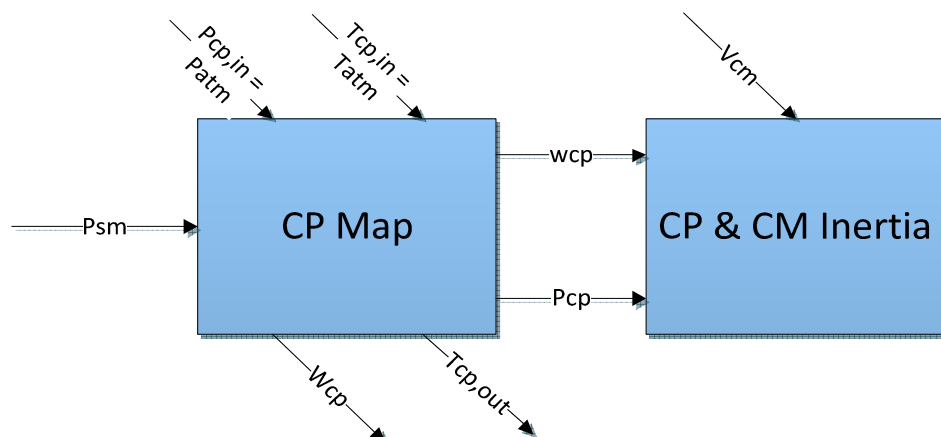


Figure 8-2 Compressor model inputs and outputs

The inputs to the model include

- Inlet air pressure $P_{cp,in}$ (typically atmospheric pressure)
- Inlet air temperature $T_{cp,in}$ (assumed to be 25°C)
- Voltage command to compressor motor V_{cm}
- Supply manifold pressure P_{sm}
- Compressor speed ω_{cp} (this is the only dynamic state in the model).

A compressor flow map determines the compressor air mass flow rate, ω_{cp} using the pressure ratio across the compressor and the speed of the compressor. This is not ideal for dynamic system simulations and could be an area in which to develop the VFCS in the future. A non-linear curve fitting method is used to model the compressor characteristics as standard interpolation routines are not continuously differentiable and extrapolation using this technique would be unreliable. Variations in the compressor inlet are reflected using corrected values of mass flow rate and compressor speed within the compressor map [97].

The compressor efficiency η_{cp} is drawn from a lookup table expressing the efficiency of the compressor from mass flow rate and pressure ratio across the compressor. The compressors maximum efficiency is 80%.

8.2.2 *The Manifold*

The lumped volume associated with the pipes and connections between each device is represented in the model as the manifold. This incorporates connections between the fuel cell, compressor, cooler and humidifier. The pipeline at the fuel cell stack exhaust is represented as the return manifold.

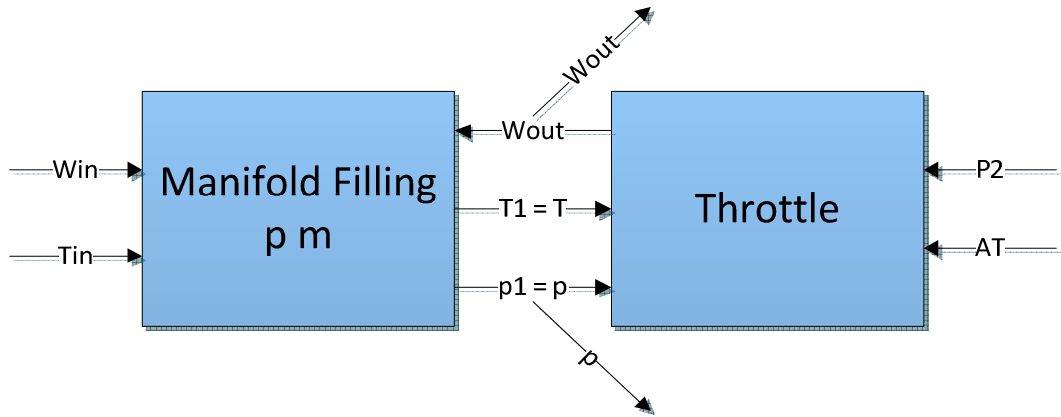


Figure 8-3 Lumped manifold model inputs and outputs

8.2.3 Supply Manifold

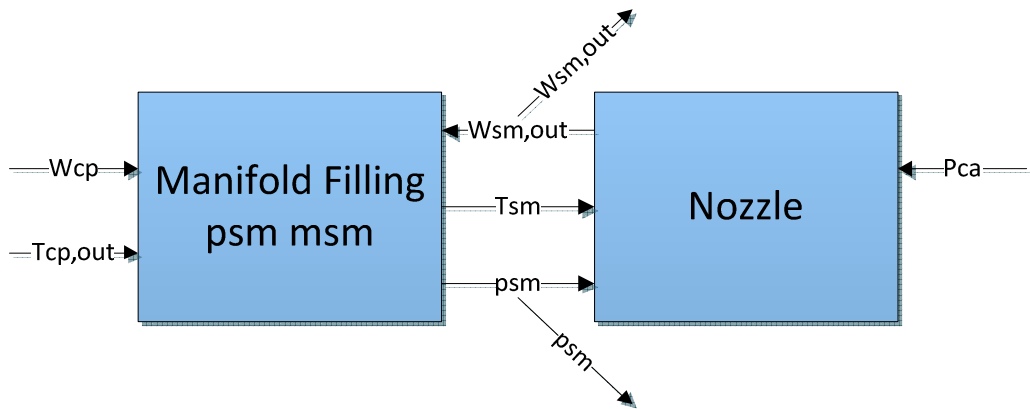


Figure 8-4 Supply manifold model inputs and outputs

The inputs to the model include

- Mass flow rate into the model W_{in} (W_{cp})
- Temperature of air in the compressor $T_{cp,out}$
- Pressure at the cathode P_{ca}

The air temperature within the supply manifold is raised as it leaves the manifold at a higher temperature. A change in temperature will increase the pressure in the manifold as the volume must remain constant. The temperature within the manifold is calculated from the mass and pressure in the supply manifold using the ideal gas law ($pV = n\bar{R}T$ where n is the number of moles and \bar{R} is the universal gas constant)

The model outputs include

- Mass flow rate out of the model W_{out} ($W_{sm,out}$)
- Supply manifold pressure P_{sm}

8.2.4 Return Manifold

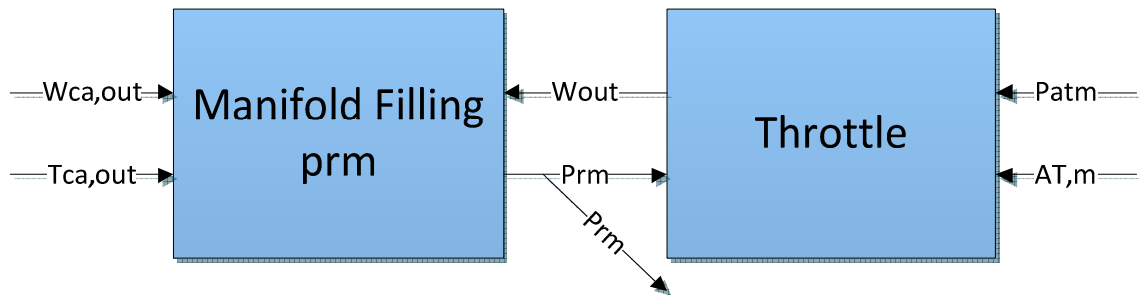


Figure 8-5 Supply manifold model inputs and outputs

In the return manifold the inputs include

- Mass flow rate out of the model W_{in} ($W_{ca,out}$)
- Temperature of air at the cathode $T_{ca,out}$
- Open area of the nozzle A_T

The changes in temperature in the return manifold are negligible as the temperature of the air leaving the stack is relatively low. The outlet flow of the manifold using a nozzle flow equation derived from [98]. The rate of flow through the nozzle is a function of the upstream and downstream pressure. This can be set as a constant or used as an extra variable to control the return manifold pressure and consequently the cathode pressure.

8.2.5 Humidifier

Air flow into the FC stack must be humidified to prevent the membranes from drying out. Within the Pukrushpan model the volume of the humidifier is small and is therefore considered as part of the supply manifold volume. The air flow is humidified by injecting water into the air stream before entering the stack.

8.3 Hydrogen supply system

In automotive applications the hydrogen supply to the fuel cell will be a tank located within the vehicle. The volume will be set and the flow from the tank regulated using a control valve. A high power demand in the fuel cell will open the valve resulting in a higher flow of hydrogen from the tank. Equally a low power demand will close the valve and reduce the flow.

The VFCS models the hydrogen supply assuming the stack is always sufficiently fed. “What-if” scenarios can be interrogated by setting the flow as a low constant (choked flow) or inputting a steady decrease in flow and pressure as if the valve were to fail or the supply of hydrogen in the tank were to be depleted [99]. The resulting decline in power can be seen in the VFCS.

8.4 Cooling system

In order to prevent damage to the fuel cell stack the air supply must be sufficiently cooled before use. The temperature of the air is typically high as it has left the compressor and leaving the air at this temperature would damage the cell membrane.

The virtual fuel cell system does not address the heat transfer effects in the model and therefore the temperature is input as a constant ($T = 80^{\circ}\text{C}$). The cooling system could be considered in further developments of the model

Chapter 9. DC-DC Converter

9.1 Introduction

The virtual fuel cell system generates a DC output. A DC-DC converter is required as an interface between the DC supply the load, giving a steady voltage output, this is particularly important in automotive applications.

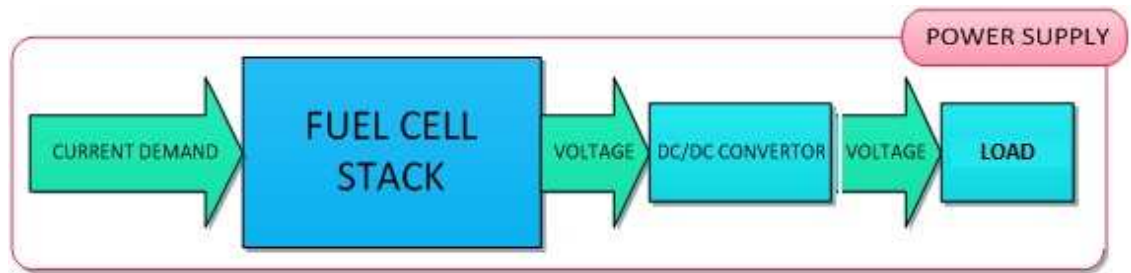


Figure 9-1 DC-DC Converter

There are a range of topologies of DC-DC converters; the most common of which can be categorized into three types: step down (buck), step up (boost), and step up & down (buck-boost). A fuel cells output voltage has a slow response to changing demands of the load. It is a necessary to include a DC-DC converter in the system to enhance the power supply and keep it at a constant level. This chapter reviews each of the DC-DC converters (buck, boost and buck-boost) with regard to inclusion in the virtual fuel cell system. It will review possible arrangements of each of the topologies within Simulink and discuss future work required to develop the model by including this DC-DC converter to produce a complete virtual fuel cell emulator for use in research and development.

For the following examples the switching period is given by T and duty cycle by D . Each arrangement includes a proportional-integral (PI) controller as a generic control loop feedback mechanism used to control the duty cycle. P depends on the present error and I on the accumulation of past errors. This calculates an "error" value as the difference between a measured process variable and a desired set point and then minimizes the error by adjusting the process control inputs.

9.2 Buck Converter

The buck topology is applied for voltage step-down and is commonly used for charging batteries. The buck converter can be represented by the following circuit diagram

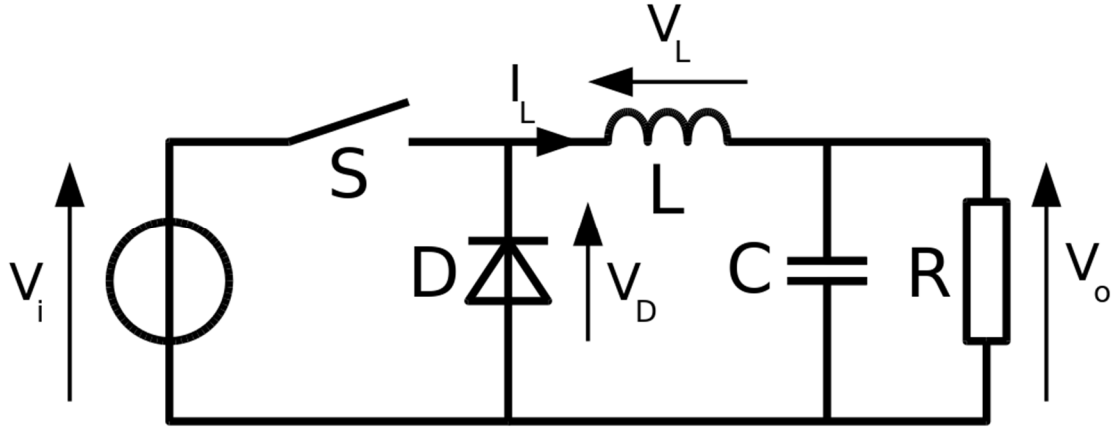


Figure 9-2 Circuit diagram showing a buck converter.

The inductor and capacitor filter the voltage so that it is not polluted. The governing equations for the buck converter can be seen by applying Kirchhoff's voltage law on the loop containing the inductor and Kirchhoff's current law on the node with the capacitor branch connected to it.

When the switch is ON the circuit is governed by the following equation,

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(V_{in} - v_o) \\ \frac{dv_o}{dt} = \frac{1}{C}(i_L - \frac{v_o}{R}) \end{cases}, 0 < t < dT$$

equation 9-1

When the switch is OFF

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(-v_o) \\ \frac{dv_o}{dt} = \frac{1}{C}(i_L - \frac{v_o}{R}) \end{cases}, dT < t < T$$

equation 9-2

Research has been carried out to assess the suitability of the buck converter for use in a virtual fuel cell system and an example of how the buck converter can be built alongside the fuel cell model can be seen below in Figure 9-3 [35].

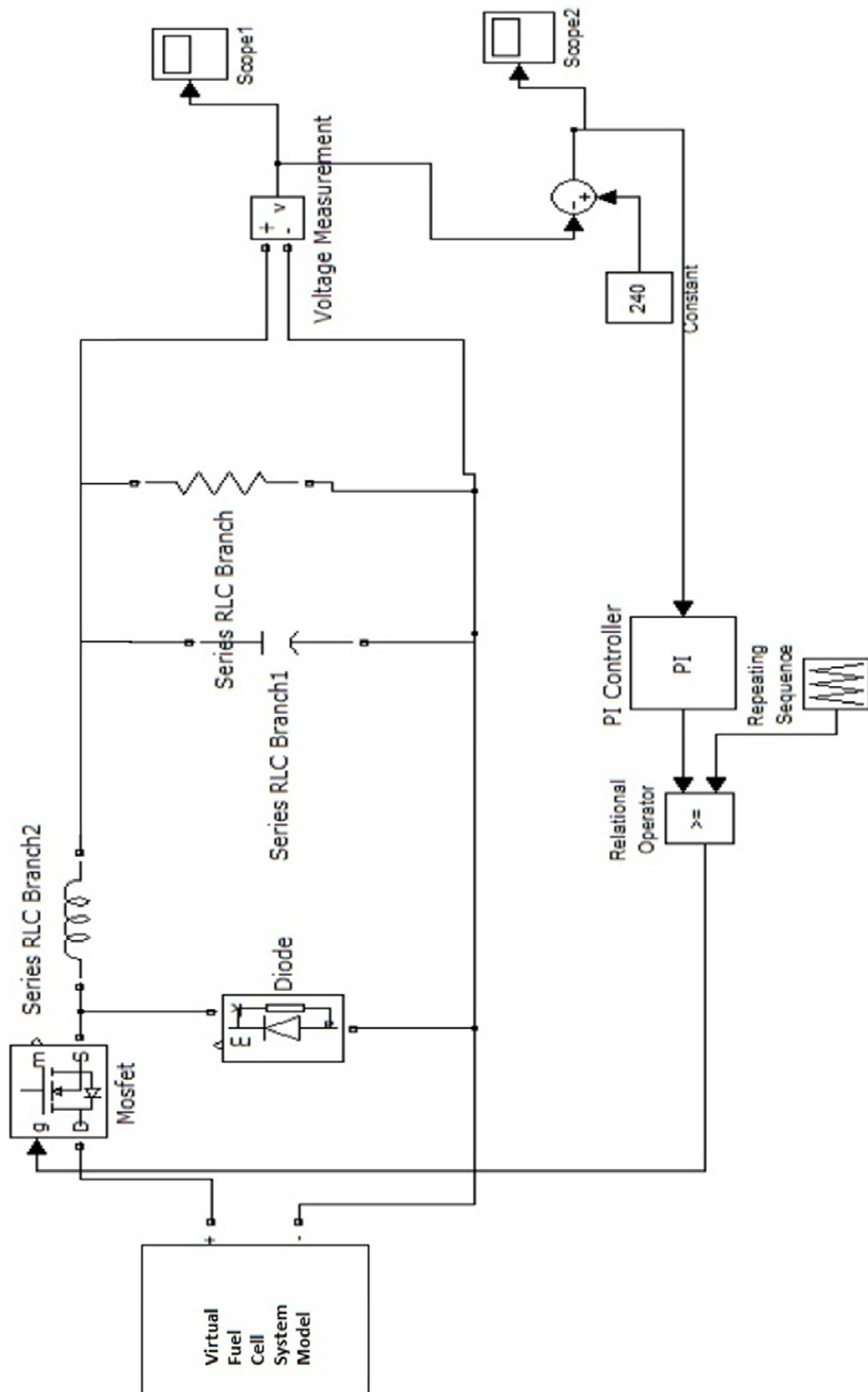


Figure 9-3 Simulink block diagram showing use of a buck converter with the MATLAB Simulink Fuel Cell Block.

9.3 Boost Converter

For stepping up the voltage a boost converter is used. This is often applied to grid-tied systems to step up the output voltage before the inverter stage. The boost converter can be represented by the following circuit diagram

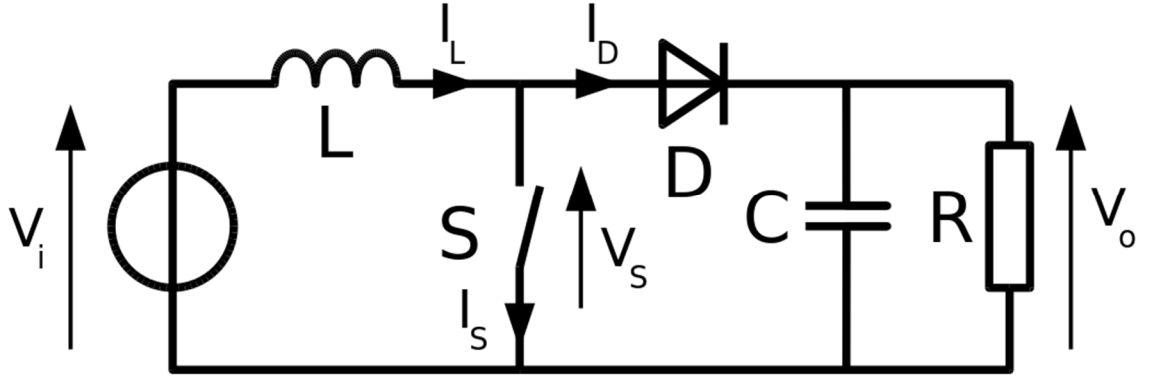


Figure 9-4 Circuit diagram showing a boost converter

When the switch is ON

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(V_{in}) \\ \frac{dv_0}{dt} = \frac{1}{C}(-\frac{v_0}{R}) \end{cases}, 0 < t < dT$$

Equation 9-3

When the switch is OFF

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(V_{in} - v_0) \\ \frac{dv_0}{dt} = \frac{1}{C}(i_L - \frac{v_0}{R}) \end{cases}, dT < t < T$$

Equation 9-4

The implementation of this converter into Simulink can be seen in Figure 9-5

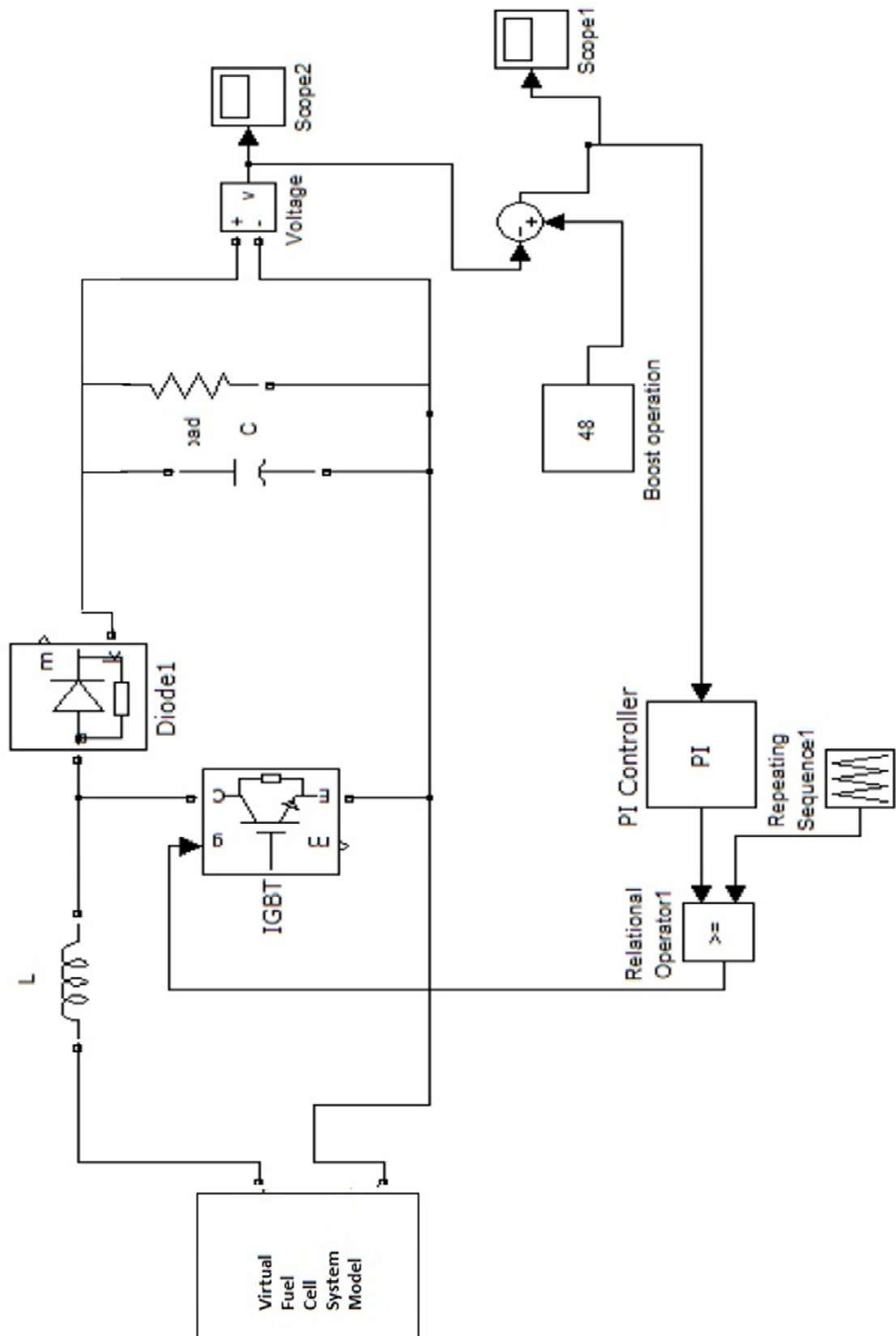


Figure 9-5 Simulink block diagram showing use of a boost converter with the MATLAB Simulink Fuel Cell Block

9.4 Buck-Boost Converter

A Buck-Boost converter is able to step the voltage both up and down and an example of which can be seen in Figure 9-6.

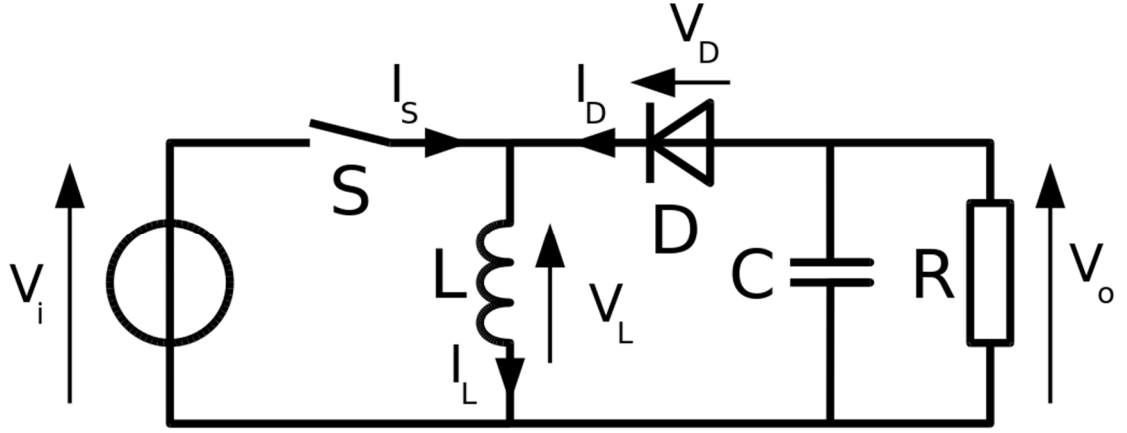


Figure 9-6 Circuit diagram showing a buck-boost converter

This could be used in the virtual fuel cell system as it gives greater flexibility in the model. Although the VFCS is modelled primarily for application in the automotive industry, inclusion of a buck boost converter keeps future development opportunities open with minimal rework required within the model.

When the switch is ON

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(V_{in}) \\ \frac{dv_0}{dt} = \frac{1}{C}(-\frac{v_0}{R}) \end{cases}, 0 < t < dT$$

Equation 9-5

When the switch is OFF

$$\begin{cases} \frac{di_L}{dt} = \frac{1}{L}(v_0) \\ \frac{dv_0}{dt} = \frac{1}{C}(-i_L - \frac{v_0}{R}) \end{cases}, dT < t < T$$

Equation 9-6

Again this has been transferred into Simulink for greater investigation however the results shown by Gupta [35] are not conclusive as to the suitability of either the buck, boost or buck-boost converter. It is proposed to include the buck-boost model into the VFCS into the future recommendations.

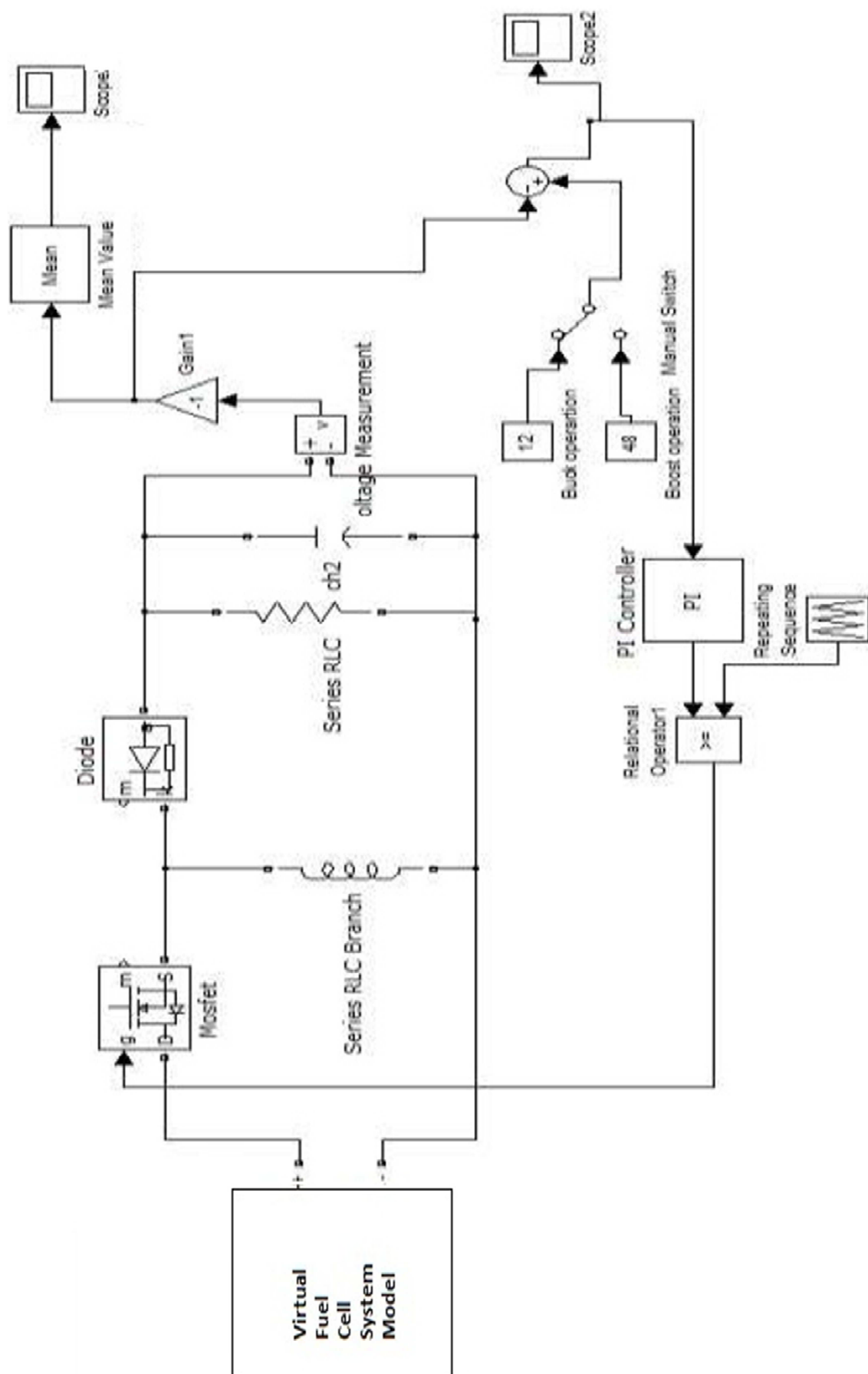


Figure 9-7 Simulink block diagram showing use of a buck-boost converter with the MATLAB Simulink Fuel Cell Block

9.5 Further Development Opportunities

Before the finished emulator can be marketed further work is required on the DC-DC converter. The most suitable would be the buck-boost topology as it builds in greater flexibility into the model. Dependant on the application of the model it could be used as either a buck converter or boost converter, opening the market from merely automotive or CHP applications.

Once the DC-DC convertor has been built into the model it should be validated against a complete system to ensure it behaves as expected. The full VFCS can then be integrated with a DC generator; resulting in a complete fuel cell system emulator.

10.1 Introduction

As discussed previously the novelty of this thesis lies in combining the Fuel Cell and its auxiliary components so that the model will run in real-time producing the same voltage output as its equivalent physical fuel cell. The build and validation of the VFCS followed the timeline shown in Figure 10-1.

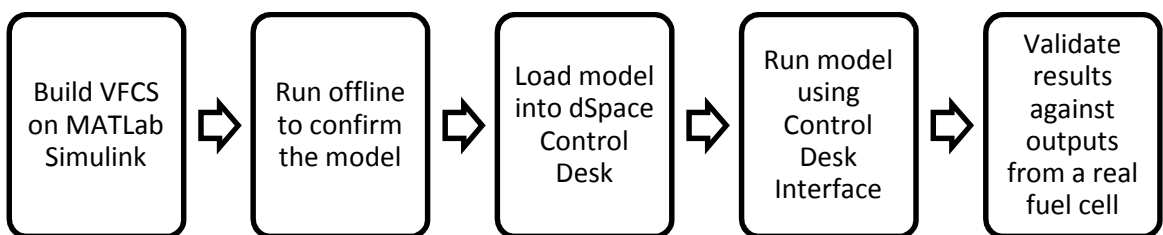


Figure 10-1 VFCS Build and Validation Plan

The Fuel Cell and components were built using MATLAB Simulink. As the final model is run in real-time, consideration was given to the complexity of the equations and what components could be assumed to remain constant. Increasing the complexity of the model in turn increases the amount of processing needed to run it in real-time.

10.2 Combining the Fuel Cell and Auxiliary Models

The Nehrir fuel cell and Pukrushpan auxiliaries were integrated to produce the complete fuel cell system model. The auxiliaries tied into the main fuel cell model using the pressure of the air supply and hydrogen supply in the auxiliary models as the anode and cathode pressure in the fuel cell, see Figure 10-2.

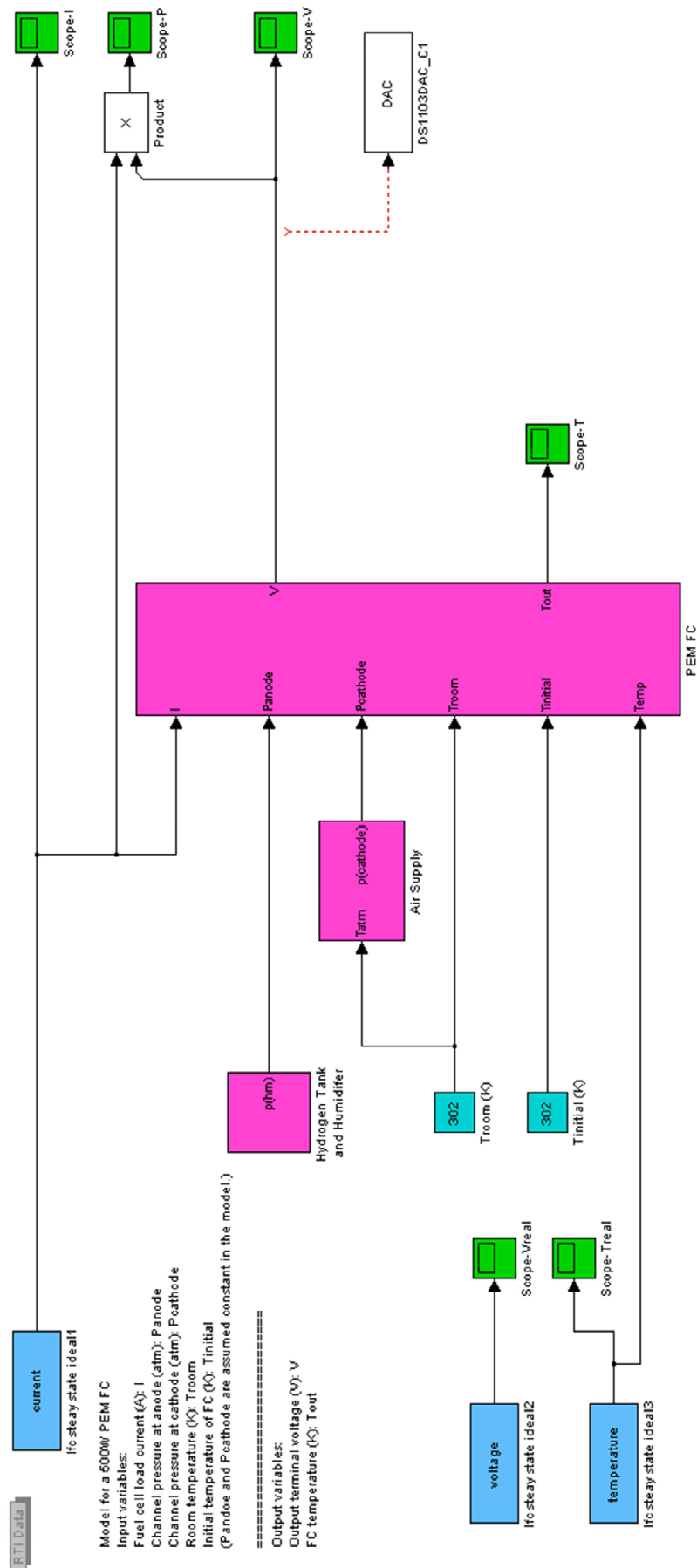


Figure 10-2 Completed VFCS

The temperature and cooling within the fuel cell was excluded from the VFCS as there are many external factors, which could affect this outside of the testing environment. Whilst collecting the validation data from the Ballard fuel cell it was clear that a cold fuel cell stack would give false readings compared to when the stack had been warmed up. If this model were to be developed further I would recommend the inclusion of the temperature control. The Ballard fuel cell monitored the temperature of the cells and using a feedback loop would adjust the cooling fans appropriately to ensure the stack did not over heat. This meant that, although the model and fuel cell were not similar the results of the fuel cell were still valid as the temperature outputs of the Ballard could be fed into the model instead of assuming the temperature to remain constant.

10.3 Running the model on dSpace.

The processor chosen to run the model in real-time was a dSpace DS1103 PPC Controller Board. This controller board is designed to meet the requirements of modern rapid control prototyping. It has the ability to work in real-time dependent on the efficiency of the code used, sampling rate and performance of the hardware. The controller can be programmed from Simulink blocks and used with a real-time interface (RTI). As with all fuel cell models a compromise was made between cost and processing power. If the VFCS were to be developed in more detail a more powerful processor would be required to keep the model running in real-time, however this would in turn increase the cost of the project.

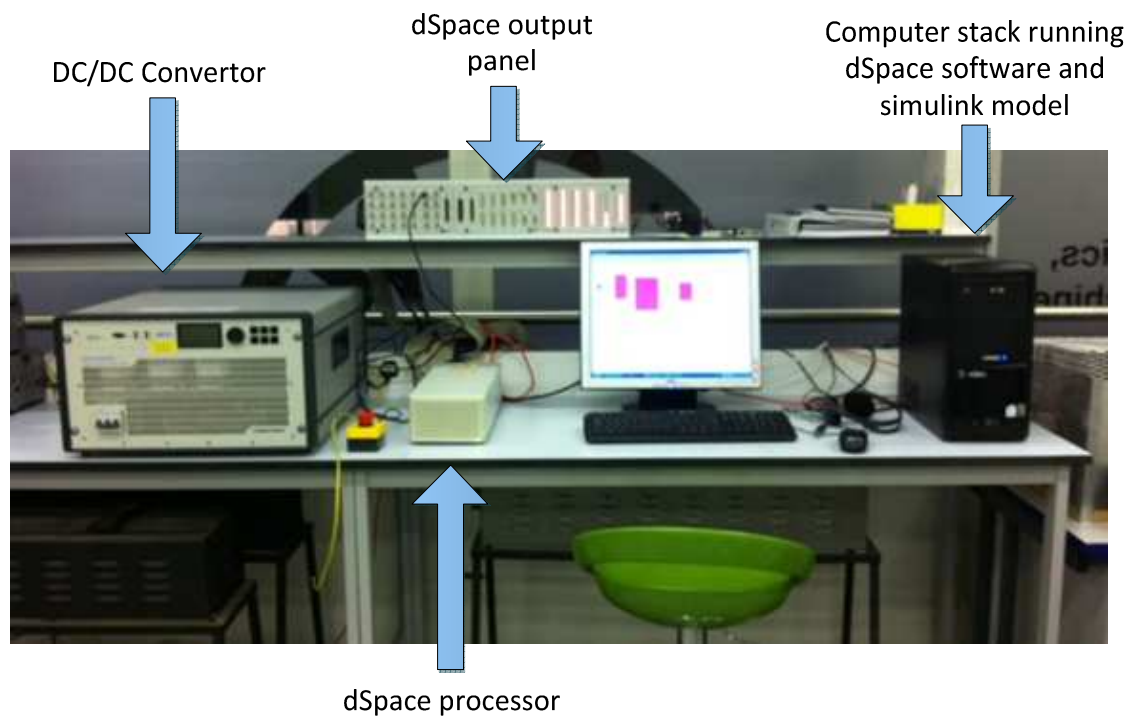


Figure 10-3 dSpace processor and PC set up

10.4 Real-time interface (RTI)

The dSpace real-time interface allows the user to control the model and make adjustments as it operates in real-time [100]. This includes the length of time the simulation runs for, frequency of readings and type of solver. The more complex a solver chosen, the more computationally intensive the program will be and therefore will require more time to execute. Simulink provides a set of explicit fixed-step continuous solvers. The solvers differ in the integration method used to compute the state derivatives of the models. Table 10-1 lists each solver and the integration technique it uses; ode1 is the least complex, therefore the quickest to execute and subsequently the most suited to real-time operation.

Solver	Integration Technique	Order of Accuracy
Ode1	Euler's Method	First
Ode2	Heuns's Method	Second
Ode3	Bogacki-Shampine Formula	Third
Ode4	Fourth-Order Runge-Kutta (RK4) Formula	Fourth
Ode5	Dormand-Prince (RK5) Formula	Fifth

Table 10-1 Simulink Solvers

These controls are particularly useful in reducing the processing power needed to run the model however increasing the fixed step size will produce less accurate results but is required to run the model in real-time.

10.5 Control Desk User Interface

Control desk is a piece of software developed by dSpace as an interface to the processor. The Simulink model is run through control desk. The user can select what outputs to monitor and inputs can be varied whilst the model is running. For example, Control desk can be used to run the FC model and part way through the simulation the user can lower the hydrogen supply, simulating the hydrogen tank emptying and choking the system.

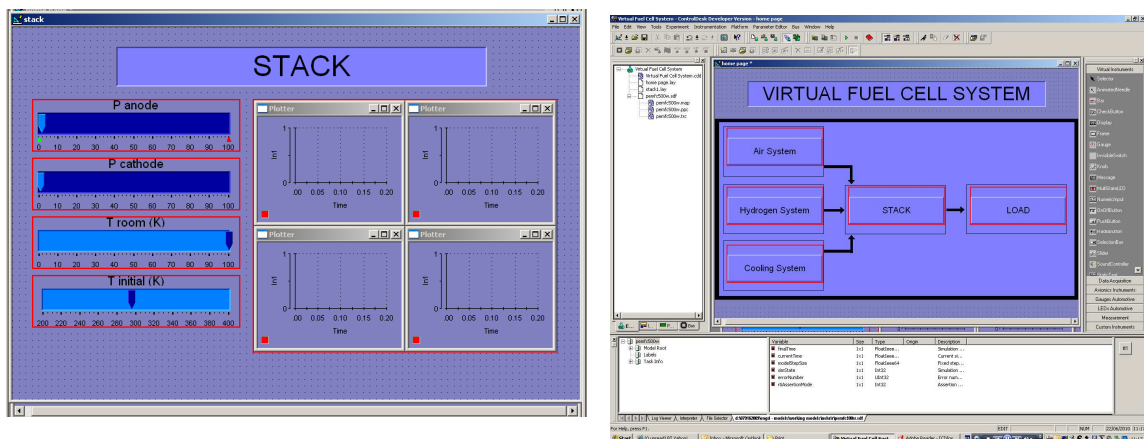


Figure 10-4 dSpace User Interface

If this VFCS were to be made into a marketable package then the graphical user interface (GUI) could be developed further so the user need only have limited fuel cell knowledge. The GUI could provide access to changing all aspects of the model that would be changed on a physical fuel cell e.g. increasing the number of cells within the fuel cell, showing how this would affect the overall output without going through the costly and time consuming task of rebuilding a physical fuel cell.

Whilst the model runs in real-time on dSpace the outputs are saved to file. These were then compared against the readings from a physical fuel cell with the same attributes programmed into the model.

10.6 Outputs of the VFCS

Once the VFCS was loaded into dSpace initial readings were taken to ensure the behavior was as expected. As can be seen from Figure 10-5 as the current is drawn from the fuel cell increases the pressure at the anode and cathode decreases as the fuel cell pulls in more hydrogen and oxygen to keep up with the demand of the system. On the right of this figure the voltage losses have been broken down into their key components; activation losses, ohmic losses and concentration losses.

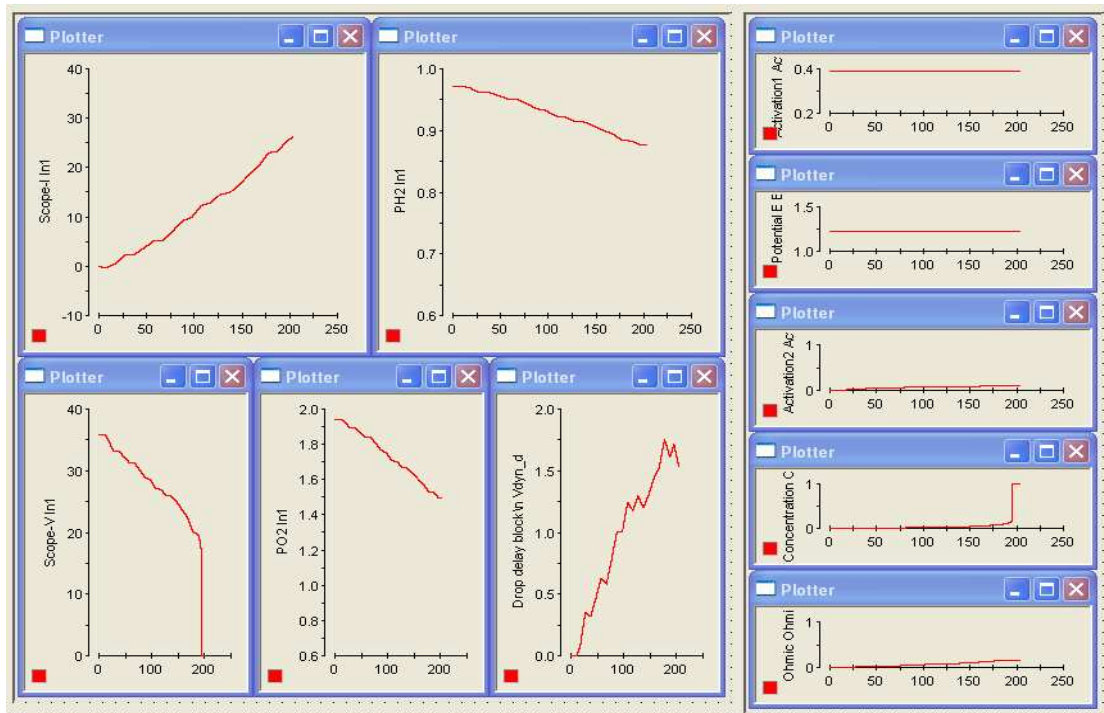


Figure 10-5 Initial Readings from the VFCS

The concentration loss was found to shoot up to 1 at 200 seconds due to a current limit set within the Simulink model. Once this was rectified the model showed to act as anticipated (Figure 10-6) and further analysis could take place. This is shown in greater detail in Chapter 11.

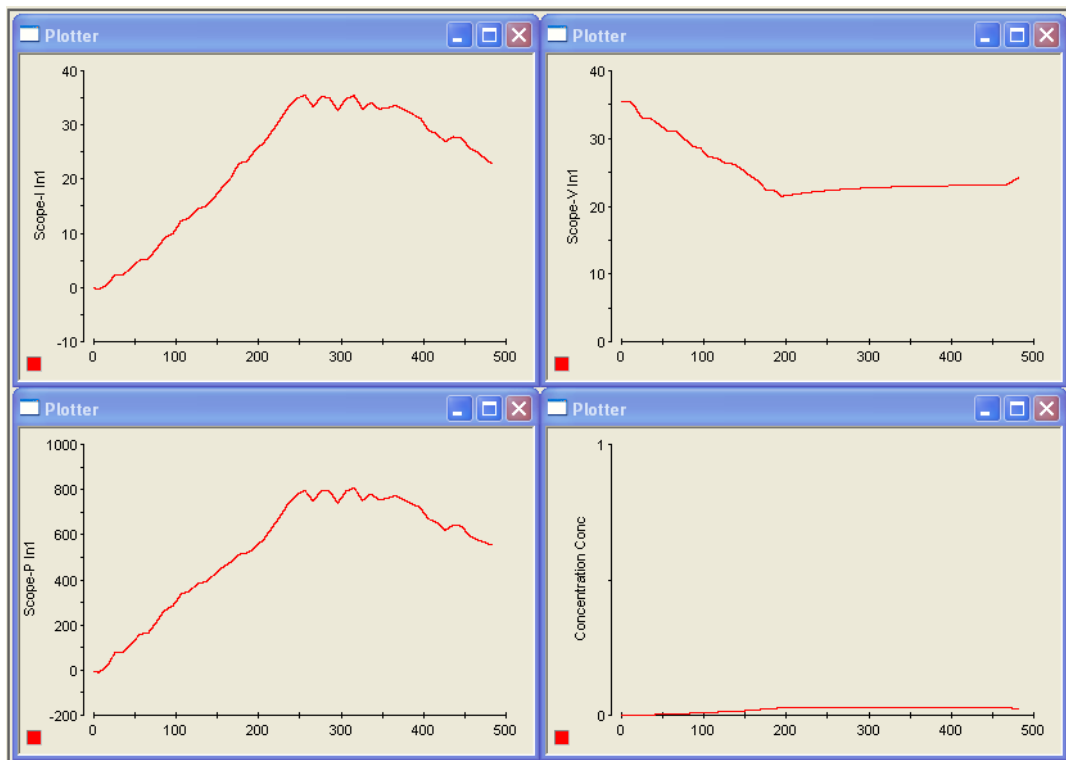


Figure 10-6 Initial output corrected for Ilim

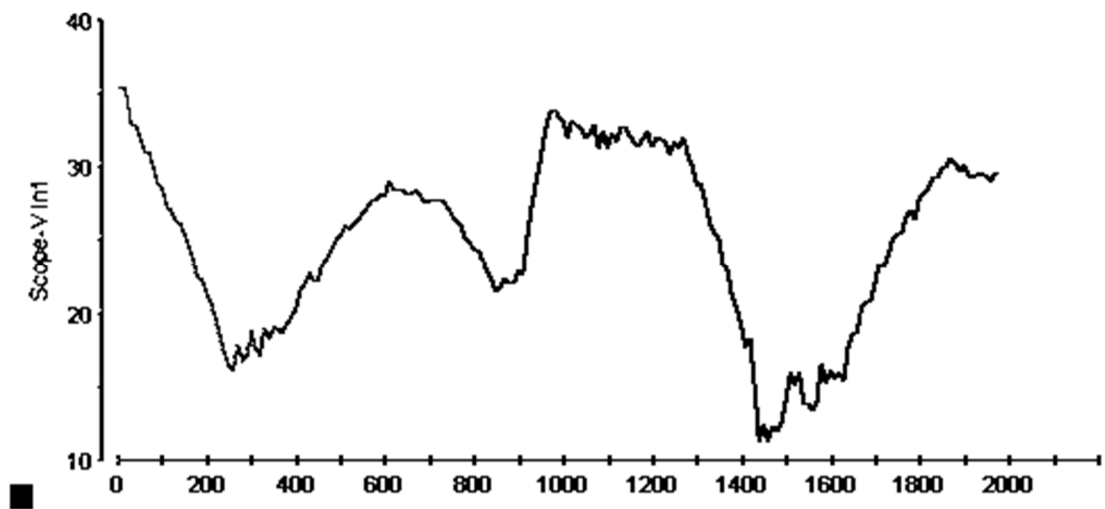


Figure 10-7 Initial voltage output plot

Figure 10-7 shows the overall shape of the plot was as expected however variations in the plot implied further discrepancies in the model to be examined.

10.7 Emulators Currently on the Market

During the initial stages of research there was only one emulator found already on the market. This was produced by MAGNUM Automatisierungstechnik

GmbH in Germany. One of their products is a Hardware-in-the-Loop (HIL) capable test bench for online diagnostics of fuel cells (Figure 10-9).

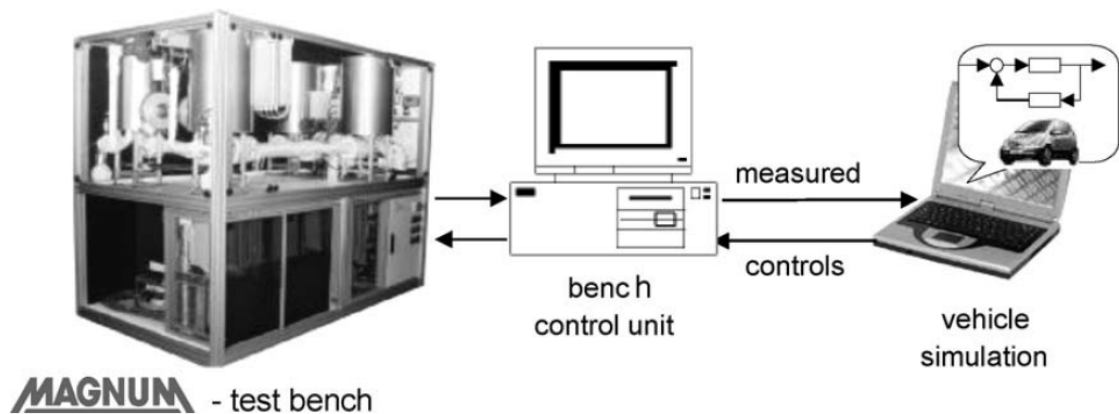


Figure 10-8 HIL Simulation of a Fuel Cell

The HIL set-up allows virtual testing of fuel cell systems where one or more components are replaced by their parameter sets (Figure 10-9). MAGNUM have additionally performed research into high temperature PEM fuel cells by modifying the code for the membrane in a model of their standard PEM fuel cell [101].

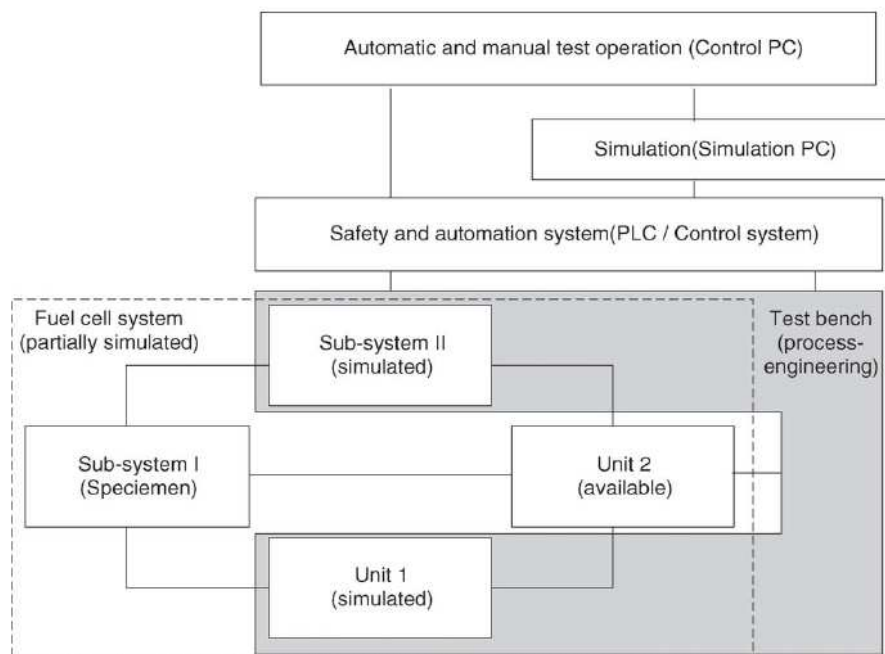


Figure 10-9 MAGNUM HIL Set up for Fuel Cells¹⁷

¹⁷ Dynamic fuel cell models and their application in hardware in the loop simulation Zijad Lemešić a,*, Andreas Vath b, Th. Hartkopf b, H. Münch a

It is evident from the number of papers published by MAGNUM (in particular Dr. Zijad Lemes) that there has been substantial background research carried out prior to launching this product. However, as the HIL test bench is ultimately a product MAGNUM wishes to profit from, there is no open code available for this system [1], only evidence of validation against real fuel cells, which show the simulation to behave well in comparison to a real fuel cell Figure 10-10.

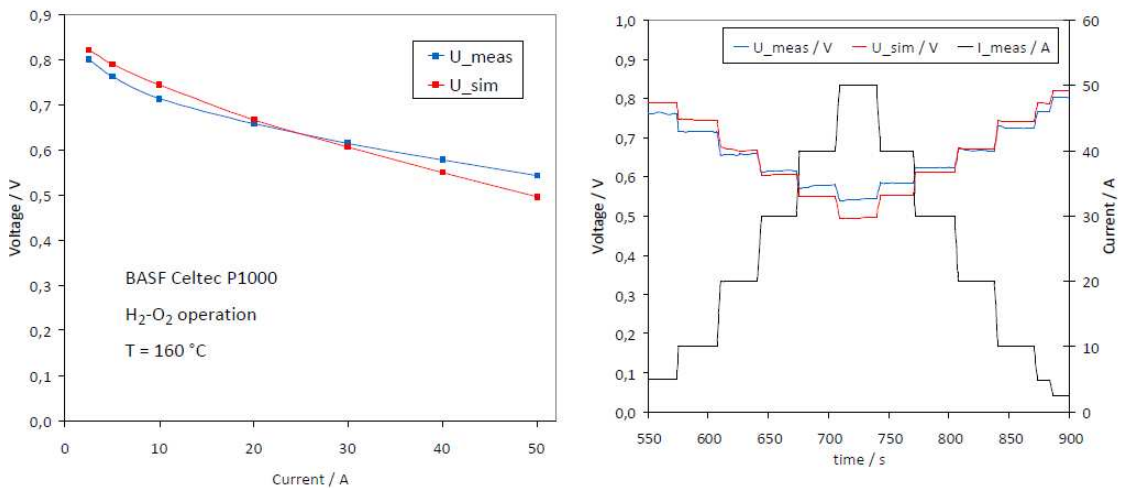


Figure 10-10 Verification of the MAGNUM model under both a) stationary and b) dynamic loading¹⁸

The MAGNUM test bed discusses its use primarily as being towards the optimisation of components within the fuel cell e.g. changing the membrane component. The VFCS presented in this thesis looks more at utilising fuel cells currently on the market to assess their suitability to a given application rather than modifying the fuel cell on a component level. This shows a marked difference in application and desired market as the MAGNUM would be best suited to OEMs (Original Equipment Manufacturer) whereas the VFCS is better suited to downstream markets looking to utilise already proven technology.

Another way this VFCS differs from the MAGNUM model is the intended output from the model. As shown clearly in Figure 10-8 the MAGNUM provides its output for automotive applications purely as a computer simulation. The goal of the VFCS is to produce an emulator which can then be used to directly power a

¹⁸ "Online Diagnostics for Fuel Cells using Hardware-in-the-Loop capable Test Benches"
MAGNUM Fuel Cell

vehicle in place of a fuel cell, allowing testing of the vehicles auxiliary components before a fuel cell has been purchased (see Figure 1-1).

Chapter 11. Model Validations

11.1 The Ballard Nexa

The 1.2kW Nexa power module (Figure 11-1) was the world's first mass produced proton exchange membrane fuel cell (PEMFC) [102]. It is suitable for integration into a range of stationary and portable power generation applications as it is small and quiet.

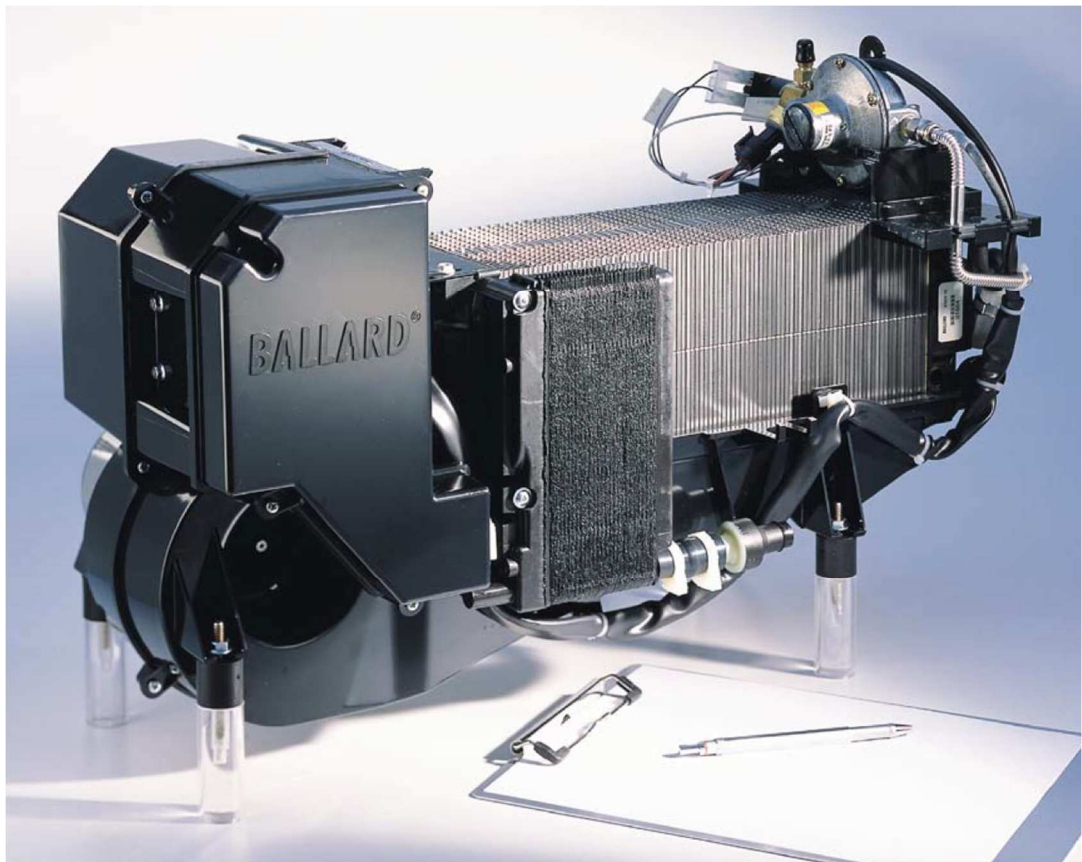


Figure 11-1 Ballard Nexa 1.2kW PEMFC¹⁹

The Ballard Nexa is a fully integrated system. It includes hydrogen supply, oxidant air supply and cooling air supply. The unit must be connected to a 24V battery for startup and shutdown [69, 103]. The Fuel Cell Controller monitors the system performance and fully automates operation by use of a control board

¹⁹ Photo from <http://www2.le.ac.uk/departments/engineering/research/electrical-power/images/1.2%20kW%20Ballard%20Nexa%20Fuel%20Cell.JPG/view>

with a microprocessor. It also includes operational safety systems making it ideal for indoor operation.

Performance	Rated net output power	1,200 watts
	Max power draw during start-up	60 watts
	Heat dissipation	1,600 watts (at rated net output)
	Current	46 Amps DC (at rated net output)
	Voltage	26 Volts DC (at rated net output)
	Lifetime	1,500 hours or 500 cycles
Fuel	Gaseous hydrogen	99.99% dry
	Supply pressure	70 – 1720kPa (g)
Operating Environment	Ambient temperature	3-40°C
	Humidity	0-95%
	Indoor//Outdoor	Unit must be weather protected.
Emissions	Pure water (vapour and liquid)	Max 25fl/oz per hour
	CO, CO ₂ , N _{ox} , SO ₂	0ppm
	Noise	72dBA at 40"
Physical	Dimensions	22" x 10" x 13" (56 x 25 x 33 cm)
	Weight	27lbs

Table 11-1 Ballard Fuel Cell Parameters

Figure 11-2 shows the important interface connections to the Fuel Cell Controller. The unit is supplied with hydrogen, oxidant air and cooling air and it releases exhaust air, water and coolant air from fans.

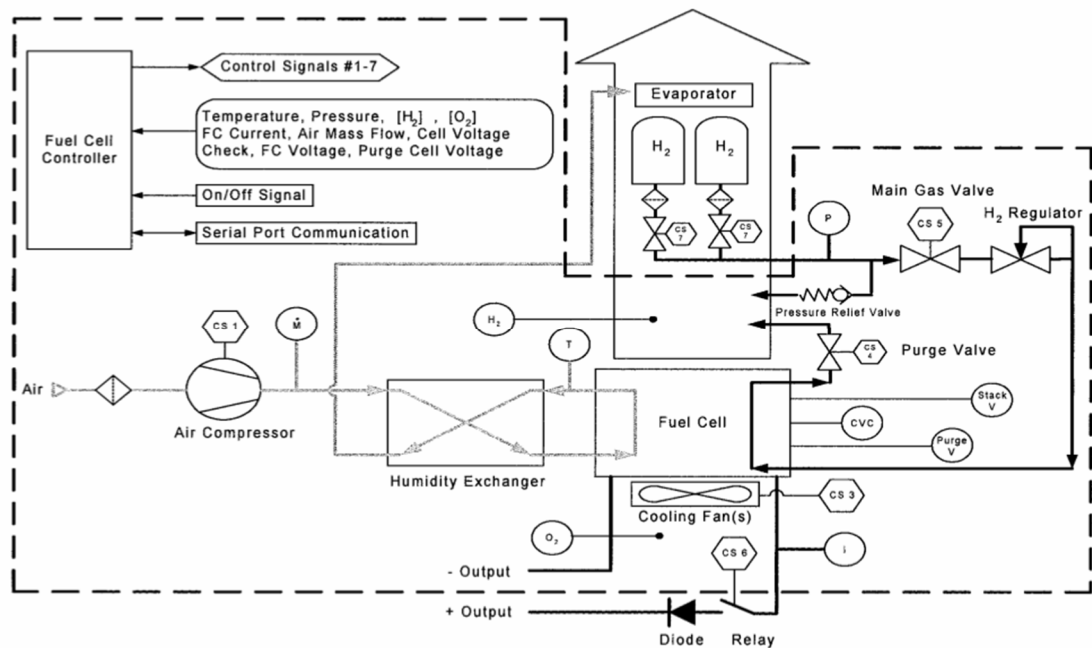


Figure 11-2 Ballard Fuel Cell Schematic

The Nexa fuel cell comprises of a stack of thin, fuel cell elements held together in series, it is these, which provide the necessary electrical power. Each individual cell produces about 1V at open-circuit and about 0.6V at full current output. The Nexa fuel cell stack has 43 cells. The Fuel Cell Controller can monitor the performance of individual cells and establish if any cells are not performing [104].

11.2 Validation Set Up

In order to validate the model the results were compared to the outputs of the Ballard Nexa. The fuel cell was primarily validated using a trial profile from the Ballard (see Figure 11-3 and Figure 11-4). This profile included a combination of increasing and decreasing power demands alongside constant power demands. This allowed the voltage output of the physical fuel cell to be plotted alongside the model outputs, making it easier to see differences and establish any shortcomings of the model.

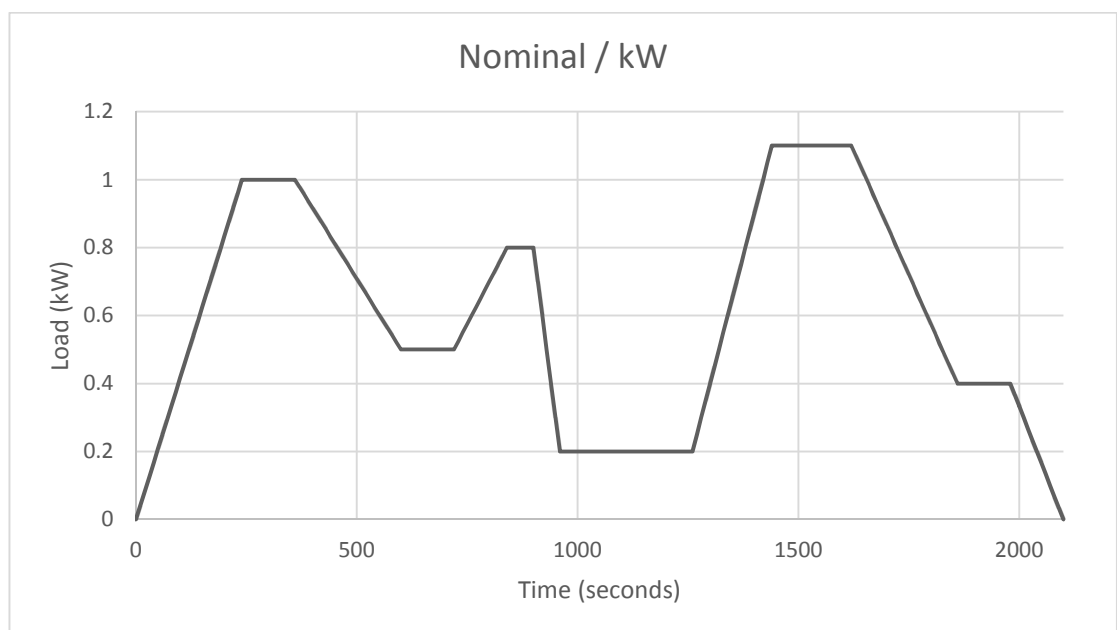


Figure 11-3 The load input into the Ballard and HILTech test bed

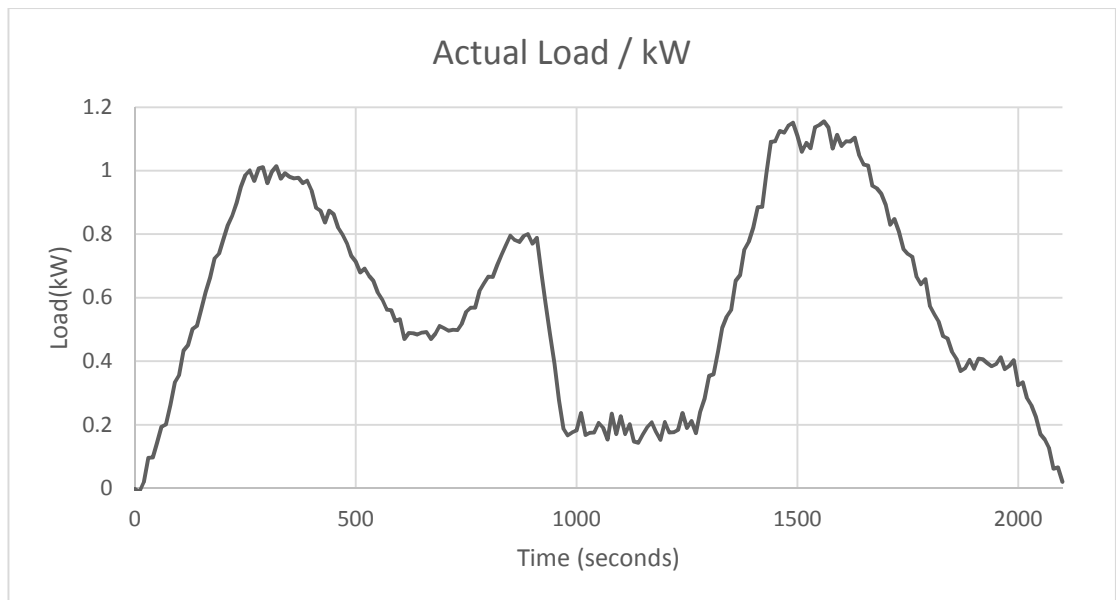


Figure 11-4 The actual load on the Ballard fuel cell.

The HILTech test bed recorded the following outputs from Ballard (see Table 11-2). From these outputs the “actual load” profile was fed into the virtual fuel cell system for validation. This profile was chosen as the readings were reflective of how the Ballard fuel cell was actually behaving, not an idealistic representation as shown in the “nominal load” profile. The profile was run over 35 minutes and readings were taken at ten second intervals. As the fuel cell has a sluggish response to changes in load demand this sample rate was adequate. A higher rate would have been of little benefit as the increase in accuracy would have required greater processing power within the model; slowing it down significantly for little improvement in calculated output.

Measurement	Units	Measurement	Units
Time	HH:MM:SS	Water Inlet	°C
Nominal Load	kW	Water Outlet	°C
Actual Load	kW	Hydrogen Pressure	bar
Efficiency	%	Methane Pressure	bar
Voltage	V	Ethane Pressure	bar
Current	A	Methanol Pressure	bar
Stack Temperature (taken at 4 locations)	°C	Air Pressure	bar
Hydrogen Temperature	°C	Hydrogen Flow	l/min
Methane Temperature	°C	Methane Flow	l/min
Ethane Temperature	°C	Ethane Flow	l/min
Methanol Temperature	°C	Air Flow	l/min
Air Temperature	°C	Water Outlet	l/min

Table 11-2 HILTech Test bed Outputs

11.3 Initial Comparisons between the VFCS and Ballard Nexa

To begin with the completed model was run in real-time with all components active in order to assess its overall performance before looking into the model in greater detail. Initial readings showed the model was inconsistent with the real fuel cell outputs at low voltage output and there was a scaling error between the two, see Figure 11-5.

Please note: within Figure 11-5 to Figure 11-11 the light plot shows the voltage output from the fuel cell and the dark plot is the output from the VFCS.

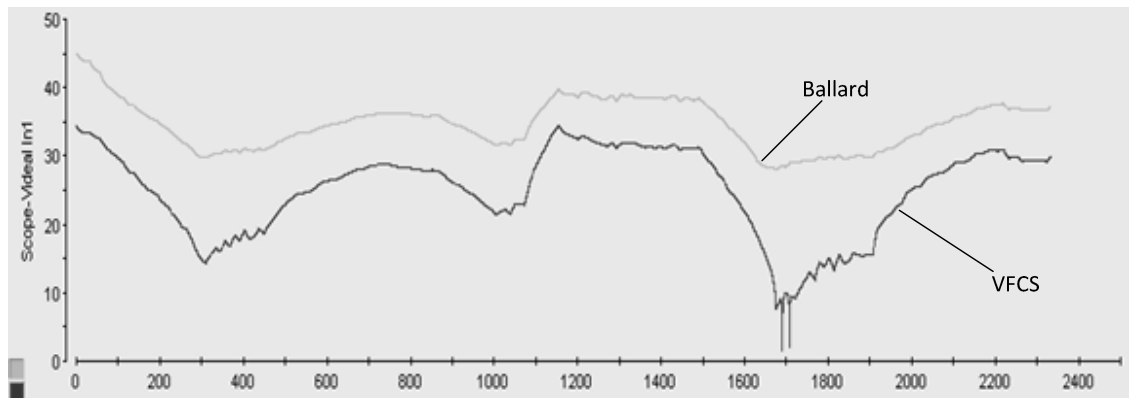


Figure 11-5 Initial errors identified within the model

11.4 Inclusion of the Temperature Output from the Ballard into the VFCS

In order to determine the root cause of these inconsistencies the first step was to introduce the temperature output from the Ballard into the model (Stack Temperature °C see Table 11-1). This better aligned the results when comparing the calculations within the VFCS to the outputs of the Ballard. The VFCS had previously assumed no changes in temperature within the model whereas in the Ballard the temperature had increased over the course of the profile (see Figure 11-6)

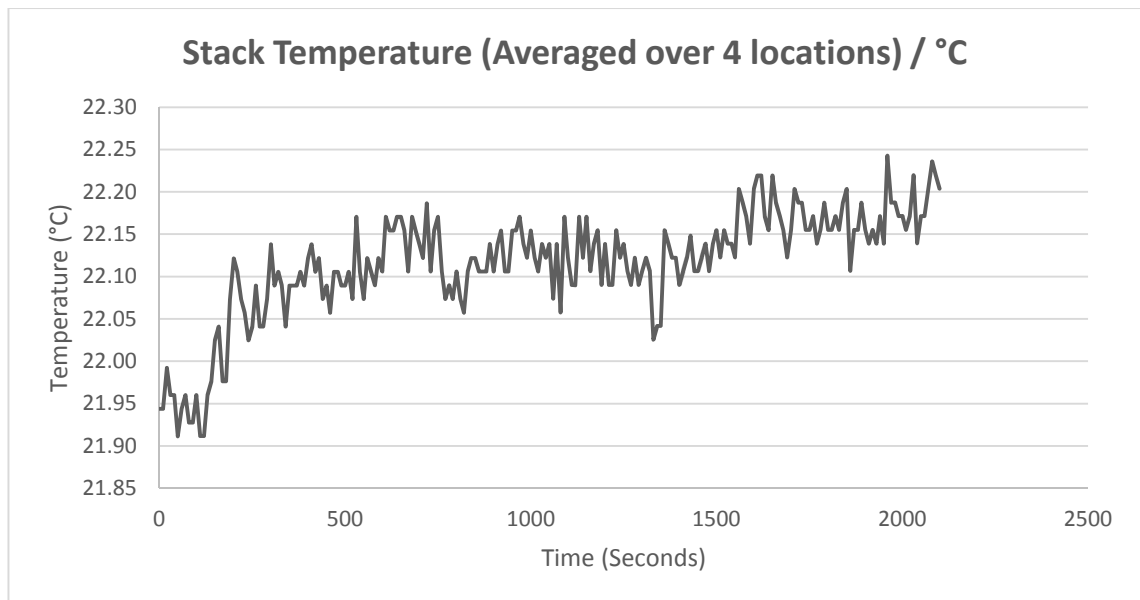


Figure 11-6 Averaged Temperature Readings from the Ballard Nexa.

A greater temperature means the particles in the fuel cell have more energy. This increases the reaction rate resulting in a higher fuel efficiency and voltage output within the fuel cell. The result of including the temperature meant the model profile was more aligned to the Ballard output. As the temperature has a great bearing on the behavior of the fuel cell, this was to be expected. This smoothed the profile and highlighted the overshoot in the plots when reaching peaks and troughs of the voltage, however the model still showed instability at lower voltages.

11.5 Variation of the Number of Cells within the Stack

Next the number of cells was increased to see if that brought the model back in line (Figure 11-7). The number of cells was increased from 43 to 56 as this aligned the starting voltages of the two plots.

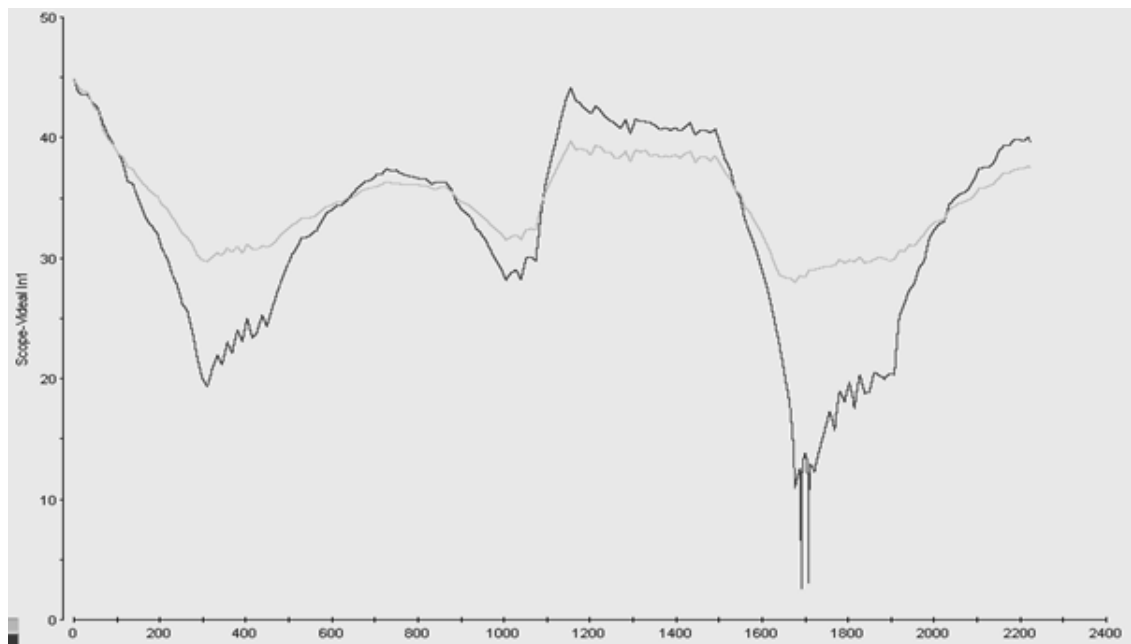


Figure 11-7 Effects of increasing the number of cells

The resulting plot showed higher voltages at peaks and lower voltage outputs at the troughs and the model was still unstable at the lower voltages.

It is important to note here that increasing the number of fuel cells did not consider the effects of increasing the size of the cells themselves. (An increase in the size of the cell increases the surface area, giving a greater area for the reactions to take place without the associated losses of merely increasing the number of cells.)

11.6 Reviewing the Voltage Loss Components with the Model

Next the model was run without inclusion of the voltage losses (Figure 11-8). It can now clearly be seen that the model was no longer unstable at lower voltages.

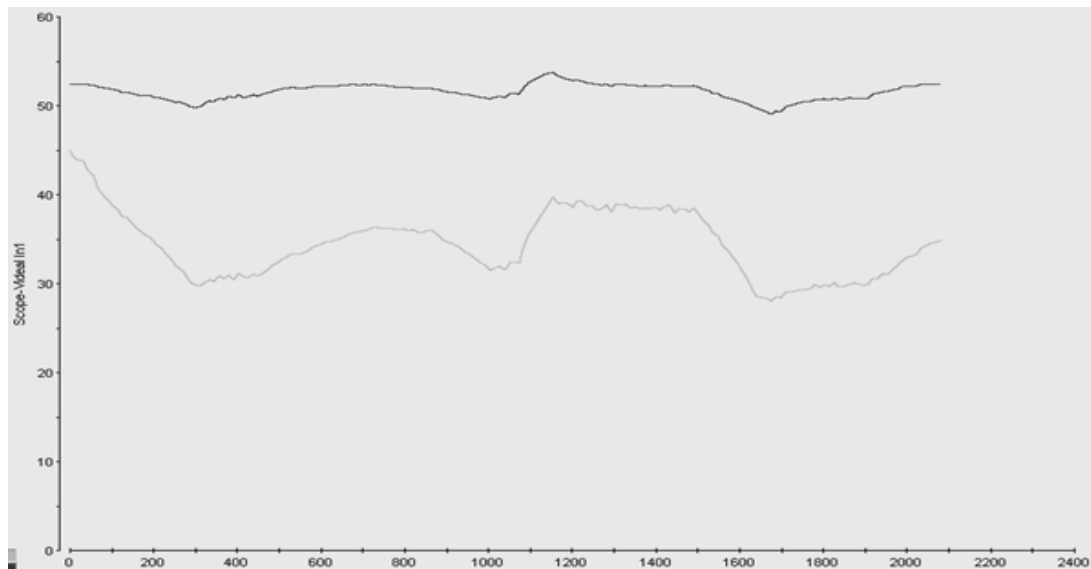


Figure 11-8 Running the model without voltage losses

The shape was good although the voltage generated was too high and did not vary over the voltage range as anticipated. This did however show that the problems within the model were generated from the voltages models calculated within the FC model.

The voltage losses were fed back into the model one by one to assess the effects, firstly the activation voltage (Figure 11-9)

11.6.1 Activation Losses

Inclusion of the activation losses brought the plot back in line with Ballard plot.

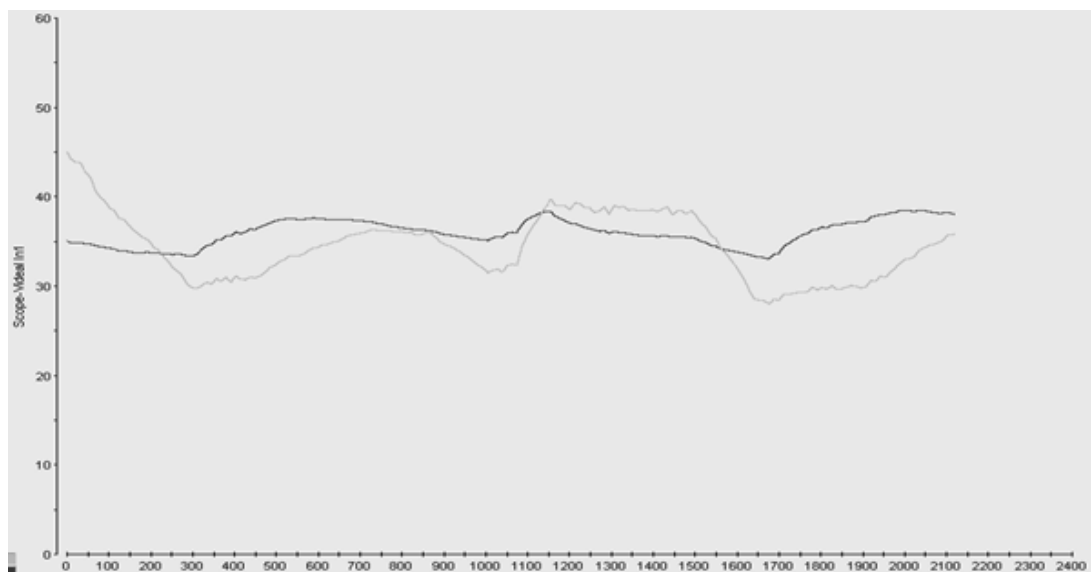


Figure 11-9 Voltage plot with activation losses.

When comparing this with Figure 3-10 (shown previously and included below for ease) it is evident that the model is behaving in line with a physical fuel cell.

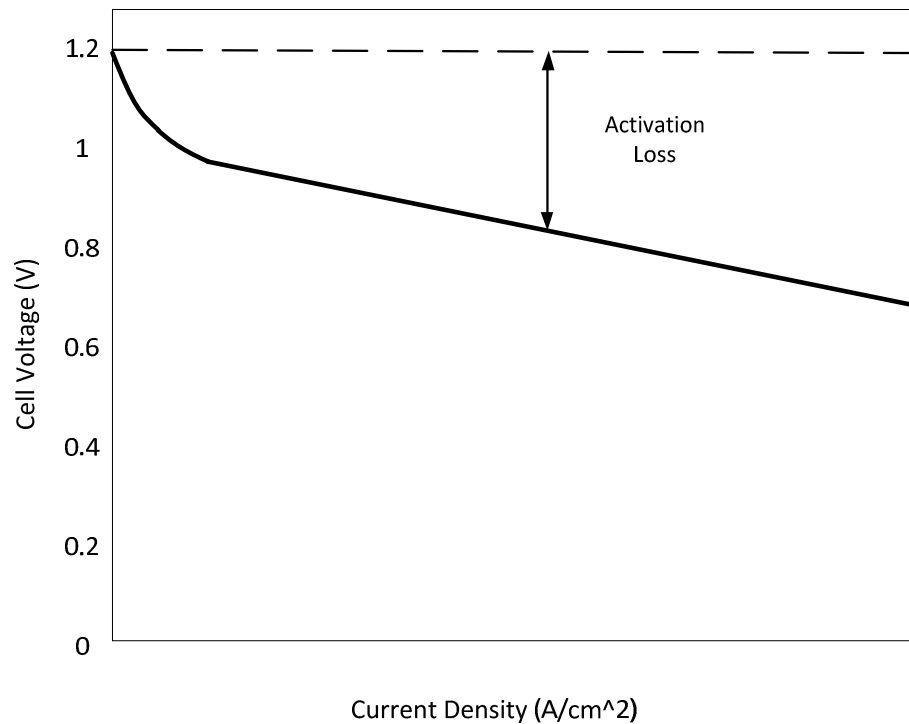


Figure 3-10 Activation Losses within a Fuel Cell

The activation loss is around 33% when the current density is above 0.1 A/cm^2 , the loss of voltage in the model follows this same trend with the voltage moving down the scale by 17V.

11.6.2 Concentration Losses

Next the activation losses were removed and the concentration losses were fed into the model (Figure 11-10). It was unmistakable from viewing this plot that this was causing the discrepancies at lower voltages.



Figure 11-10 Voltage plot with concentration losses

Comparing this with the plot for concentration loss (seen previously in Figure 3-12) indicated that when the current was high the current density was exceeding $1.5\text{A}/\text{cm}^2$ and therefore introducing errors within the model.

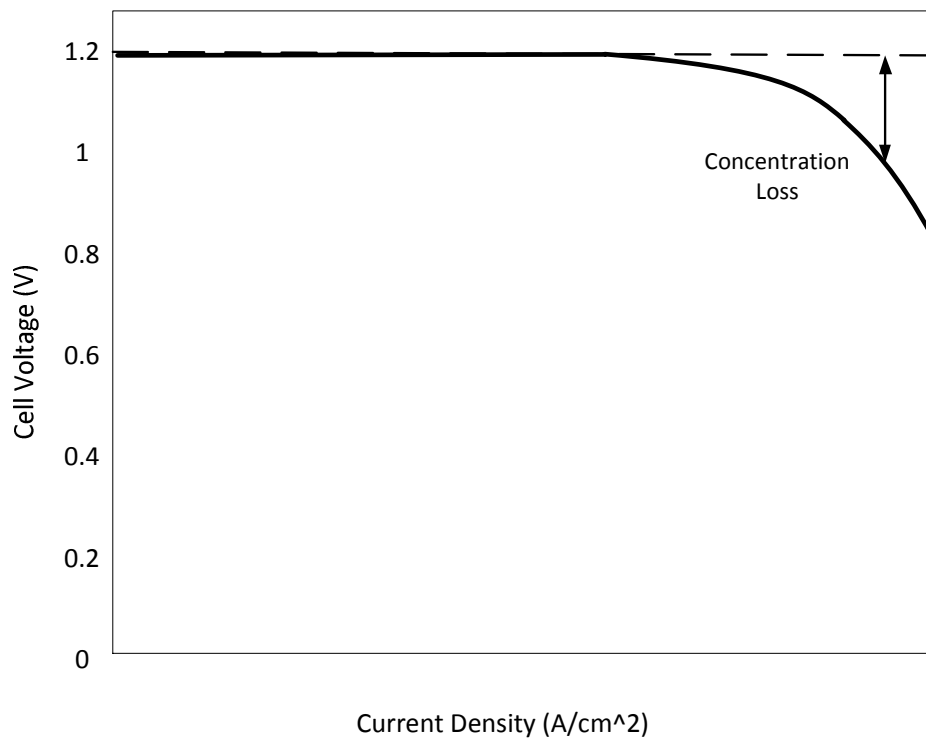


Figure 3-12 Concentration Losses within a Fuel Cell

This showed there to be errors in the setup of the fuel cell and on further investigation it was found that the area of the cells had been input incorrectly. This was then added to the input page on dSpace to ensure later users of the model could not repeat this error.

Correcting the area of the cells in the stack and feeding all the voltage losses back into the model gave the plot shown in Figure 11-11.

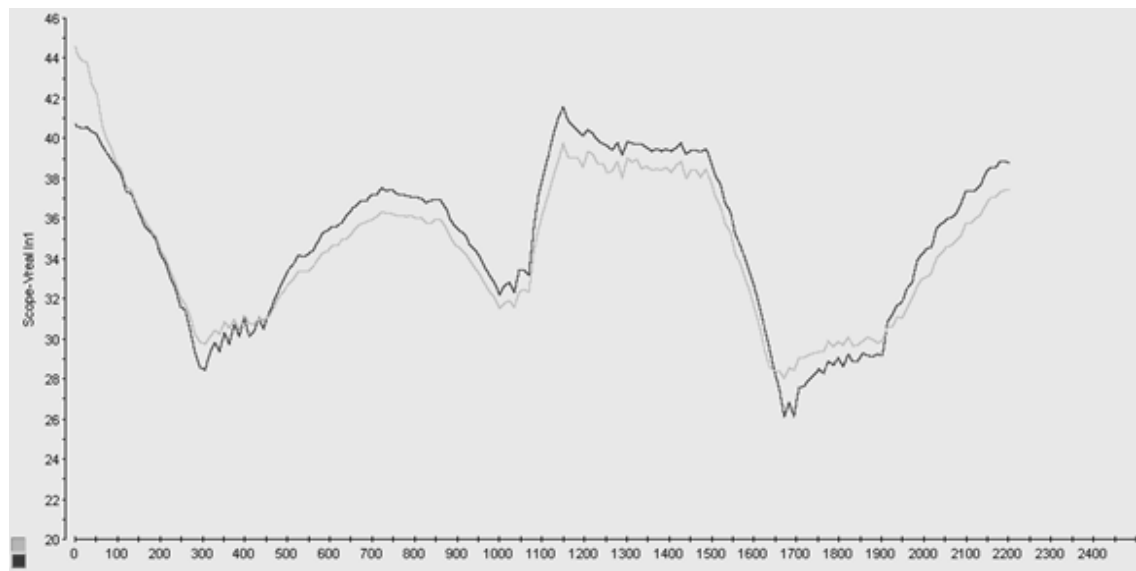


Figure 11-11 Finalised model output

Although the area of the fuel cell is not given within the Ballard data sheet this shows it is an important factor for the user to establish before the model is run to ensure reliable results.

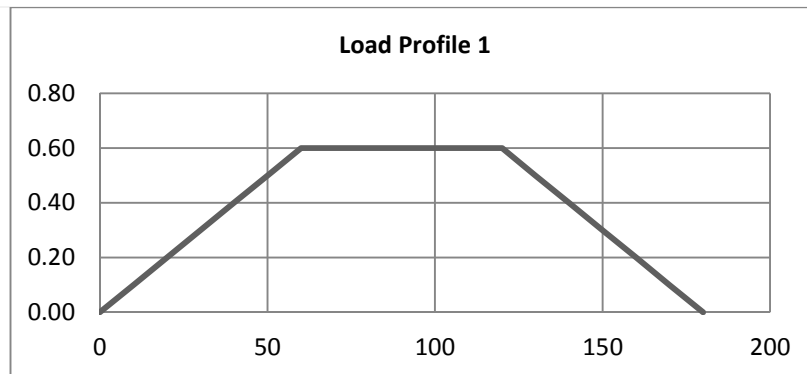
11.7 Test Conditions

The fuel cell readings were taken over the course of one week. The fuel cell was set up on the HILTech test bed and the apparatus, once set up remained unchanged to aid continuity of results. The fuel cell was run for 60 minutes each day to ensure all the components were warmed up and check for spurious results. This included running varying load profiles holding the fuel cell at low loads for extended periods of time. Each of the load profiles was run 3 times and an average taken.

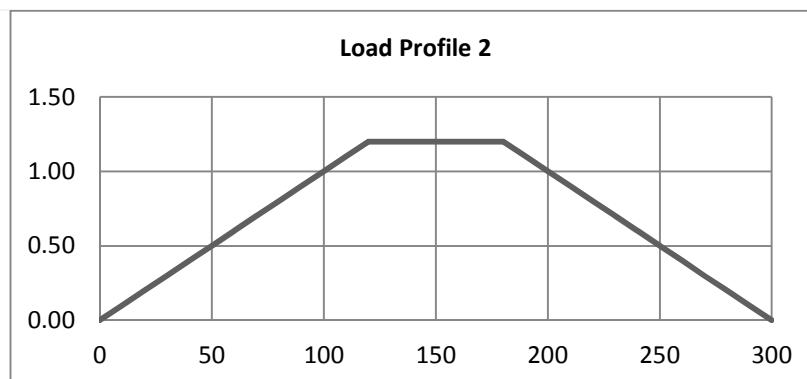
11.8 Comparison of Load Profiles

Eighteen variations were loaded into the fuel cell model and their outputs directly compared with the Ballard. The eighteen load profile were as follows (Full outputs can be found in Appendix 13-A)

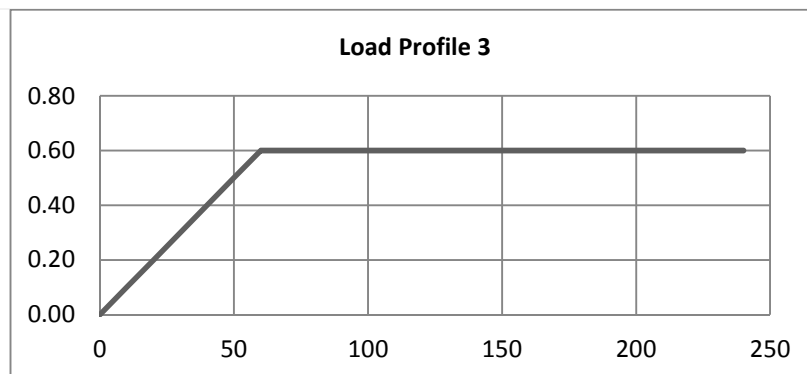
For all graphs x axis is time in seconds and y-axis is power in kilowatts.



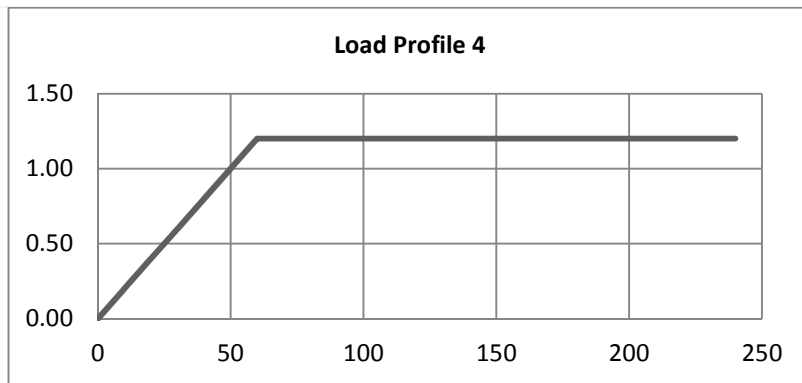
Profile 1 is a simple ramped profile increasing linearly over 60s to 0.6kW, holding that load for 60s before return to zero over 60s.



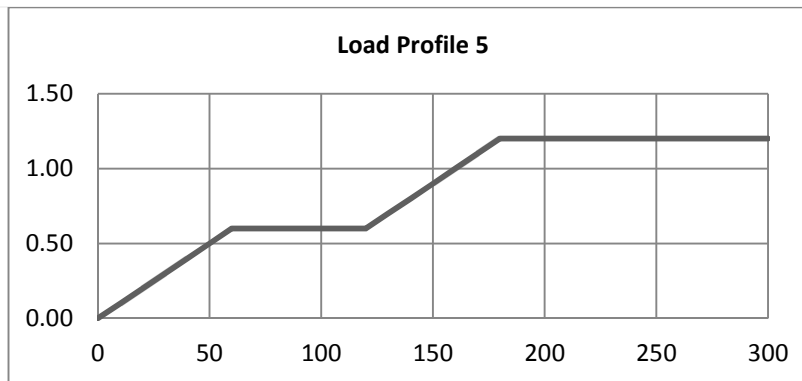
Profile 2 is a scaled version of Profile 1. The peak load however is 1.2kW but the rate of increasing load remains the same.



Profile 3 is ramped up to 0.6kW at the same rate as the previous profiles however the fuel cell is held at this peak power.



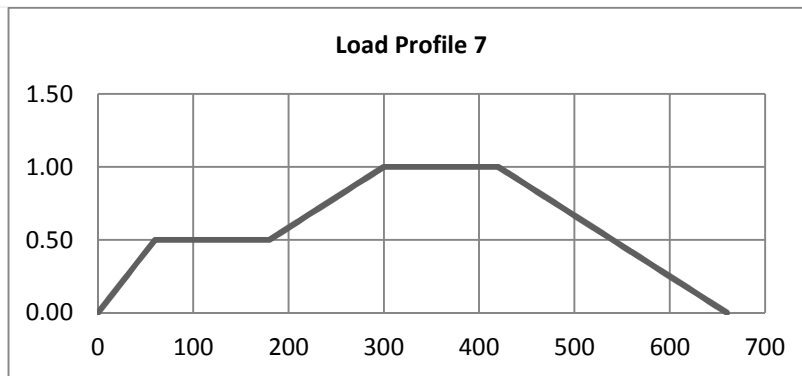
Profile 4 is ramped up to 1.2kW over 60s and held at this value.



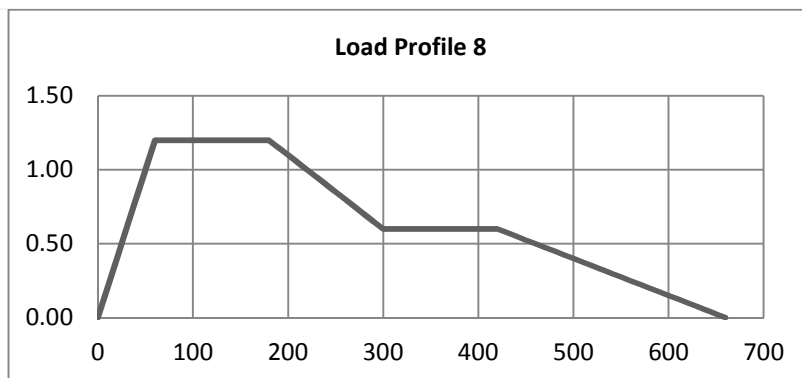
Profile 5 is ramped up to 1.2kW in stages. Once it reaches 0.6kW it is held for 60s before moving up to the full 1.2kW.



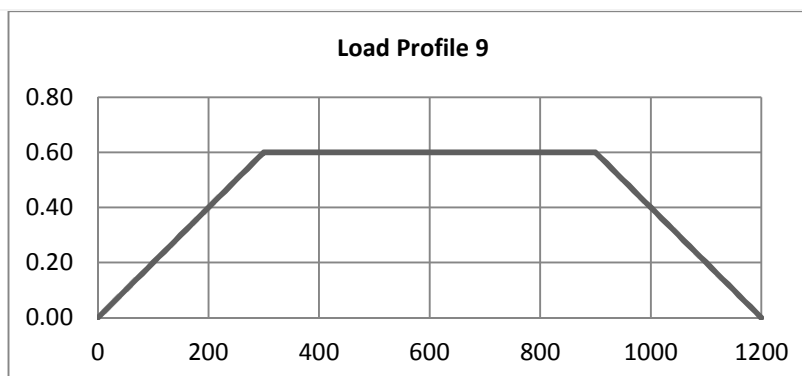
Profile 6 looks at the effect of reducing the load to 0.6kW once it has been held at 1.2kW.



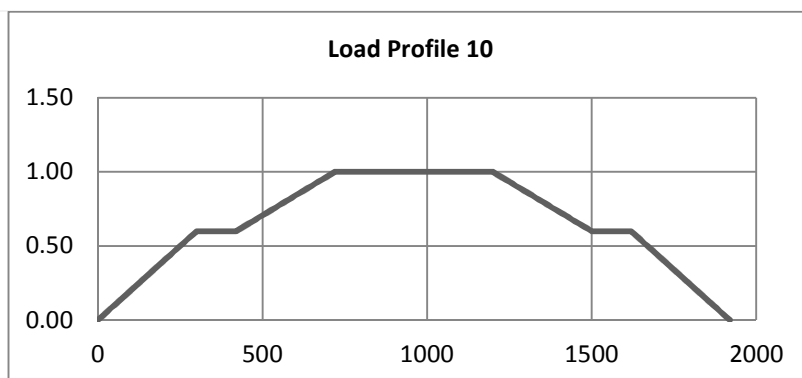
Profile 7 follows the load increase shown in Profile 5 however it peaks at 1kW instead of the maximum rated load (1.2kW). Profile 7 lasts 11 minutes and returns the load to 0kW.



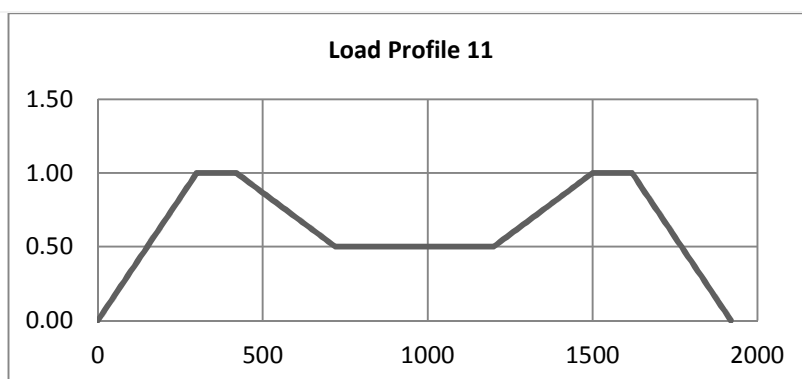
Profile 8 looks at quickly increasing the load to maximum and then reducing the load over an extended period of time.



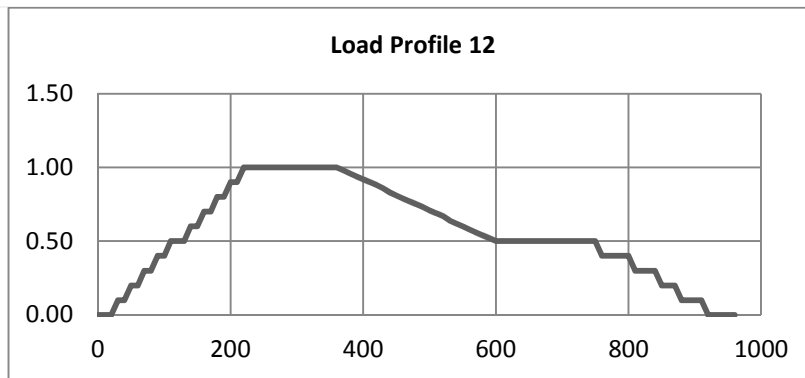
Profile 9 increases the fuel cell to 0.6kW over 5 minutes before holding it there for 10 minutes and then returning it back to 0W.



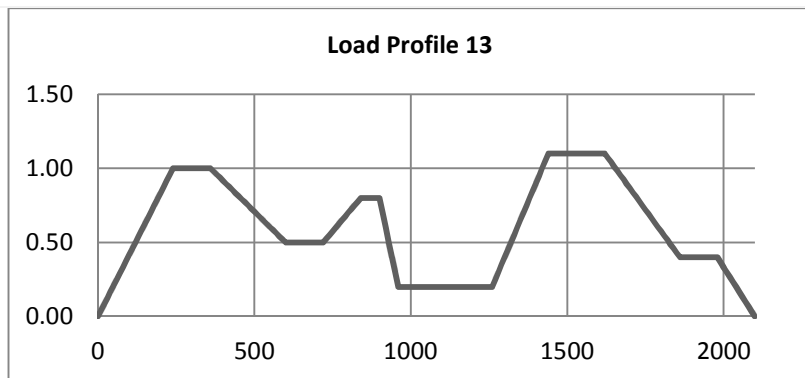
Profile 10 lasts for 32 minutes in total. The fuel cell is taken to 1kW and back down to 0 following a simple step pattern. The load reaches 1kw after 12 minutes.



Profile 11 also lasts for 32 minutes however the load peaks are inverted from profile 10.



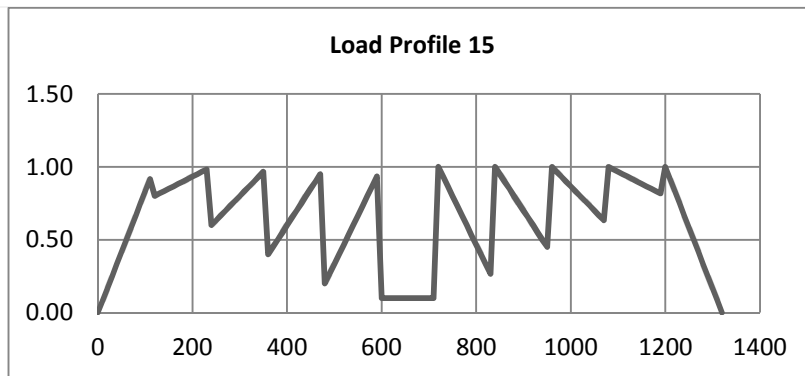
Profile 12 does not increase linearly to 1kW so one can see what happens when the demand fluctuates.



Profile 13 takes varies the demand over 35 minutes. This is the longest simulation run for the fuel cell.

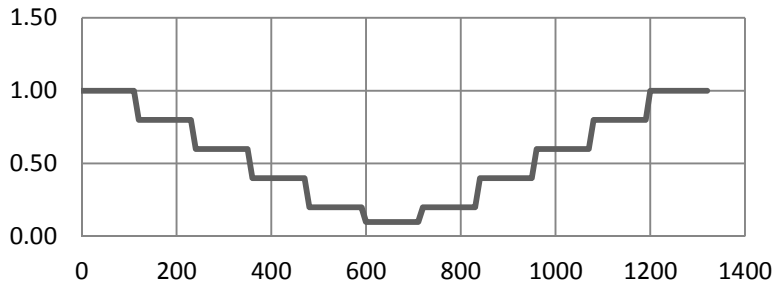


Profile 14 follows a similar demand cycle to Profile 13 however the load is not held for any time at any one value.



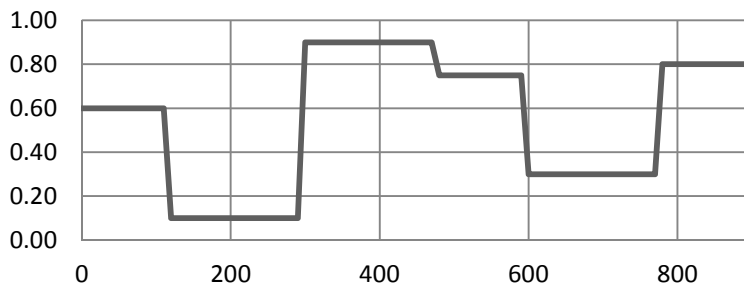
Profile 15 looks at abruptly changing the load demand on the fuel cell do the speed of response can be viewed.

Load Profile 16



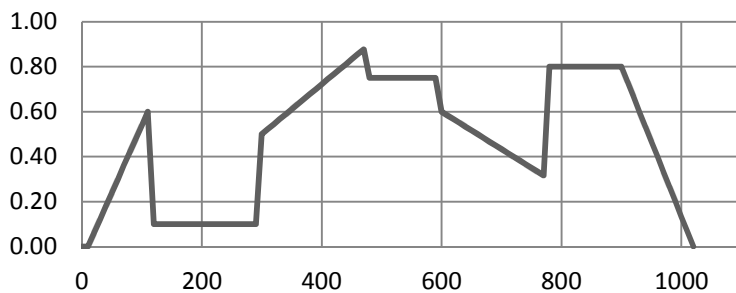
Profile 16 shows even step changes in the load, starting and ending at a high load value.

Load Profile 17



Profile 17 shows large changes in demand. The changes are abrupt but the fuel cell is held at these load values.

Load Profile 18



Profile 18 takes characteristics from all the previous load profiles and most closely represents the demands of a fuel cell in a vehicle.

Chapter 12. Conclusions

12.1 Satisfying Project Objectives

The objectives of this project were stated in chapter 1.1 and shall be addressed one by one

1st. Objective ***Investigate current fuel cell models to establish which would be most suitable for use in real-time simulation.***

The number of fuel cell models available is ever growing. The key parameters that separate these are an important factor to consider when selecting a suitable fuel cell model. The model chosen for this project (Nehrir) was selected on its academic merits and proven status.

The auxiliaries were also chosen by selecting proven models which had been also used as a base in many others research. The Pukrushpan auxiliaries are cited in a number of research papers and provided a good outline for building the auxiliaries in the virtual fuel cell system.

Building the model in modules (fuel cell, air supply system etc...) builds in an additional flexibility when taking the product to market. If this were to be sold as a development tool it would allow the package to be sold as components; allowing the consumer to purchase multiple modules to increase the accuracy of their model or use only the fuel cell as their needs require. This also means upgrades in the software could additionally be sold as modules. Modules could be built for different system options e.g. an air cooled system or the fuel cell could be cooled by a water jacket, allowing the user to build a fuel cell system exactly reflecting their needs. This removes the reliance on assumptions within the model and eliminates the degree of inaccuracy between the results of the model and the completed physical system.

2nd. Objective *Investigate how these models could be modified for more effective use in real-time simulation.*

Real-time simulation requires either a simplified model or substantial processing power. As the virtual fuel cell system was designed with the intent of taking it to market the emphasis was put on simplifying the model and keeping costs low.

Reducing the complexity within the fuel cell model comes with its draw backs. The accuracy of the output is compromised as the model is simplified and as such the user must decide when assumptions can be made and when the output must be calculated.

In the virtual fuel cell system the model does not consider the cooling system within the model. It assumes the cooling to be adequate to keep the fuel cell operating at optimum performance. Although this assumption does not cause concern within the model or when it is validated in lab condition, this may need to be developed further in the future. If the virtual fuel cell system were to be used to validate systems in situ there is a good chance the cooling could be compromised and the ability to analyze this using the model would be advantageous.

3rd. Objective *Produce a complete model of a fuel cell system which requires minimal processing power.*

The virtual fuel cell system is a proficient model including all the main auxiliaries required in a basic fuel cell system. Following some initial teething problems the model now runs without issue on a dSpace DS1103 PPC Controller Board.

Many assumptions are introduced into the model to keep the processing power required to a minimum. These assumptions include cell temperature and membrane humidity. The balance of water within a fuel cell is a complex matter and calculating this in real-time would require additional processing capability.

4th. Objective *Validate the virtual fuel cell system against a physical fuel cell to ensure the assumptions made in order to reduce processing power to not have negative effects on the output of the model.*

The outputs of the model validation can be seen in Appendix 13-A Tables of Ballard Fuel Cell and VFCS Outputs. From these graphs it is clear to see that the model provides a good output when compared with the ideal load profile and the output of the physical fuel cell.

The assumptions included within the model, although giving the benefit of reduced processing time, have a negative effect on reliability of the results for use in research and development. The final VFCS does not allow in depth analysis of certain 'what-if' failure scenarios as the cooling system has not been included and other common failure modes are not modeled.

12.2 Recommendations for Future Work

This model could be enhanced using the following recommendations

1. Incorporating the cooling system into the model to increase the accuracy and allow the investigation of more system failure scenarios.
2. Establish the key failure modes of concern within a fuel cell system and expand the model to include these phenomena e.g. drying out of the membrane, impurities in the fuel supply or choking the fuel cell from preventing hydrogen from being fed into the fuel cell.
3. Further investigate the effects of temperature on the fuel cells to establish if this could be predicted and included in the model to create an advanced fuel cell emulator.

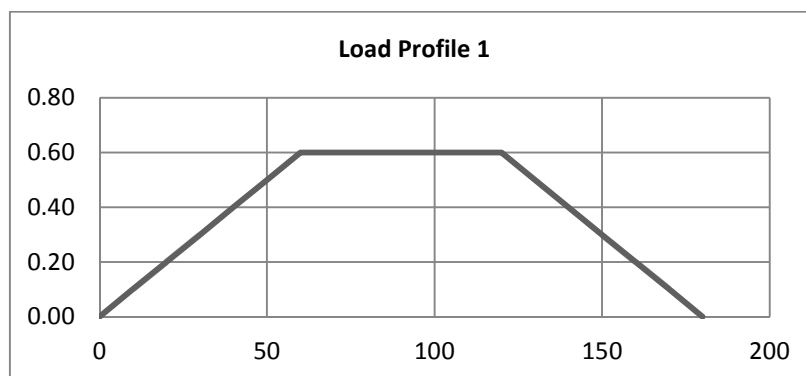
4. Integrate a DC-DC converter into the set up and validate this against a complete system to ensure it behaves as expected. The full VFCS can then be integrated with a DC generator; resulting in a complete fuel cell system emulator.
5. Develop the user interface in order to create a higher quality GUI and lock subsystems in order to protect intellectual copyright. (If this VFCS were to be marketed permission would have to be sought from Nehrir and Pukrushpan for inclusion of their models).

Chapter 13. Appendices

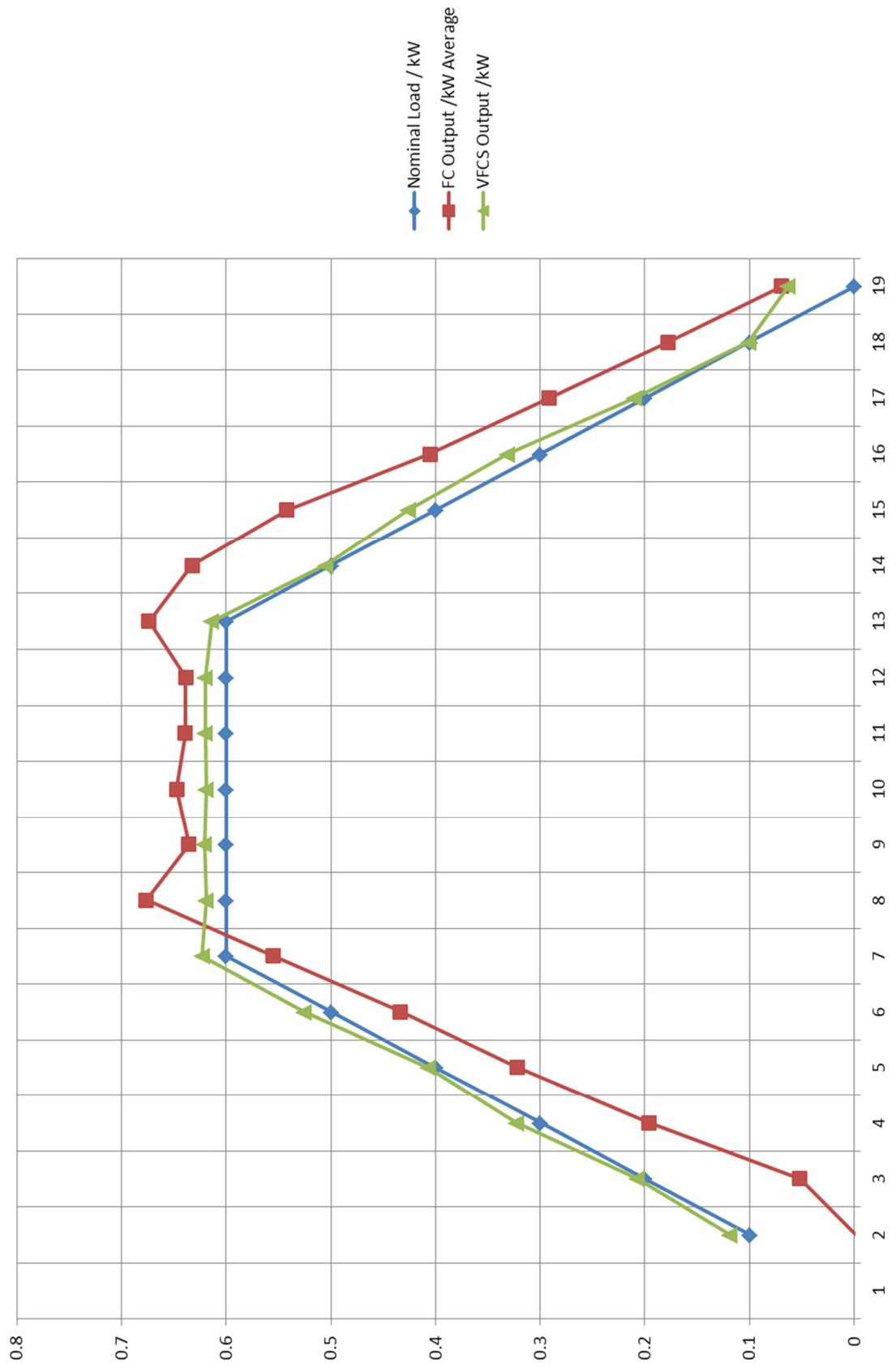
Appendix 13-A Tables of Ballard Fuel Cell and VFCS Outputs

Appendix A-1. Load Profile 1

Profile 1 is a simple ramped profile increasing linearly over 60s to 0.6kW, holding that load for 60s before return to zero over 60s.

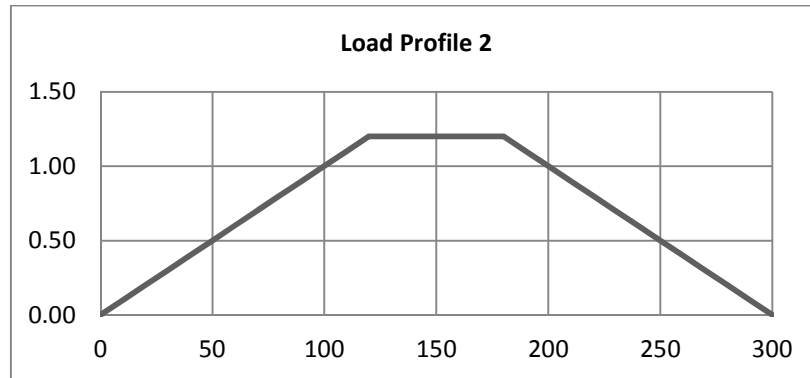


Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.10	-0.001	-0.001	-0.001	-0.001	0.119
0.20	0.043	0.058	0.054	0.052	0.207
0.30	0.190	0.208	0.190	0.196	0.323
0.40	0.327	0.319	0.319	0.322	0.407
0.50	0.433	0.435	0.432	0.433	0.526
0.60	0.535	0.569	0.561	0.555	0.623
0.60	0.677	0.679	0.673	0.676	0.619
0.60	0.644	0.629	0.634	0.635	0.621
0.60	0.629	0.653	0.659	0.647	0.619
0.60	0.618	0.649	0.650	0.639	0.620
0.60	0.650	0.633	0.634	0.639	0.620
0.60	0.688	0.668	0.666	0.674	0.614
0.50	0.638	0.633	0.627	0.633	0.505
0.40	0.540	0.545	0.541	0.542	0.426
0.30	0.408	0.406	0.402	0.405	0.331
0.20	0.334	0.273	0.268	0.292	0.210
0.10	0.194	0.172	0.167	0.177	0.101
0.00	0.065	0.075	0.068	0.069	0.063

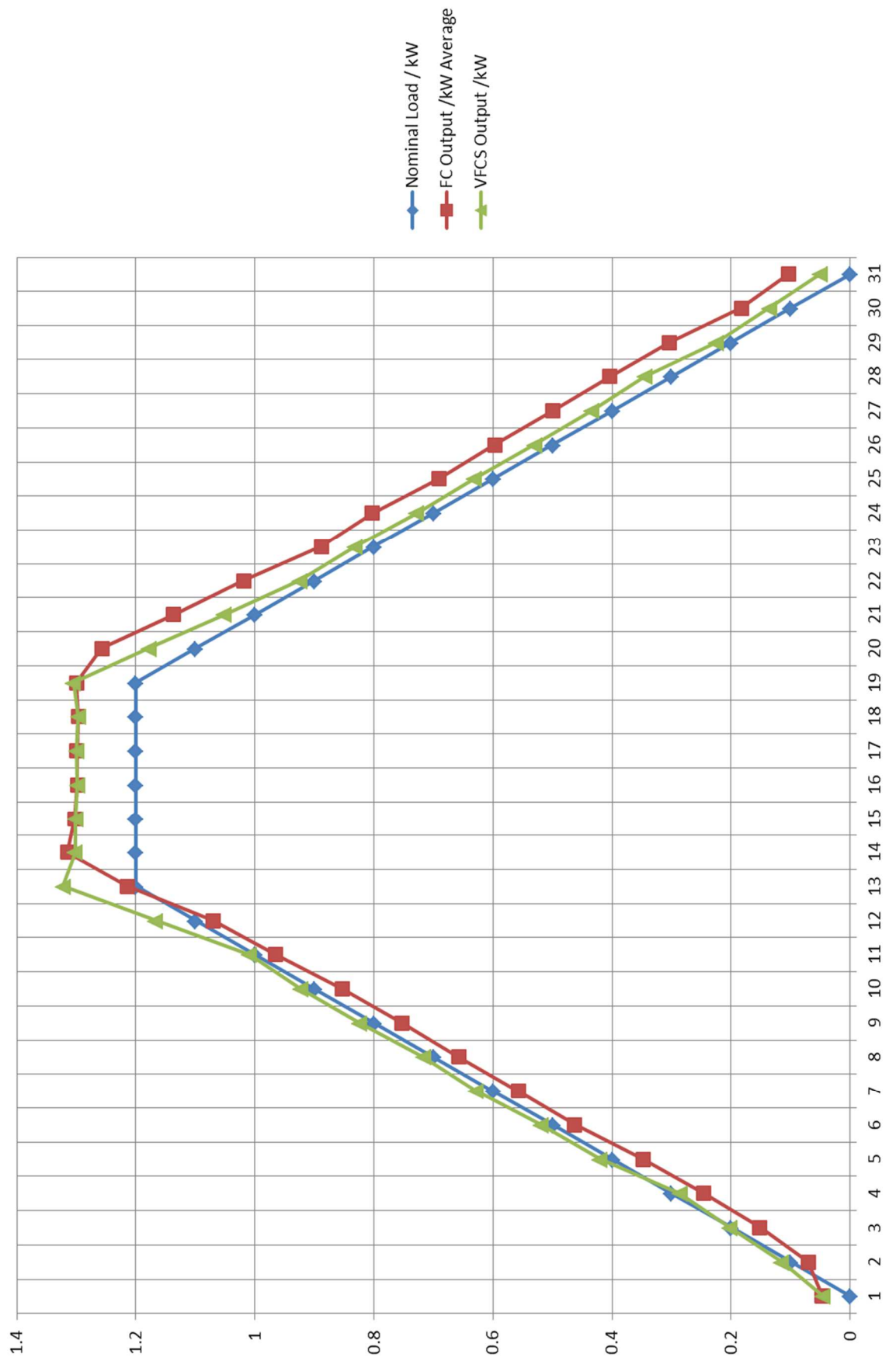


Appendix A-2. Load Profile 2

Profile 2 is a scaled version of Profile 1. The peak load however is 1.2kW but the rate of increasing load remains the same.

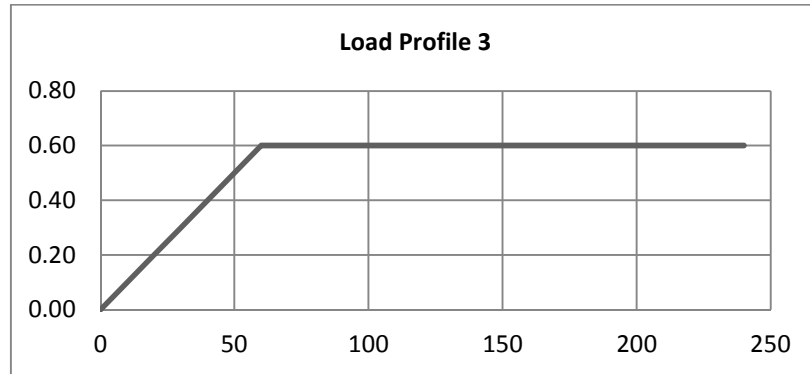


Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.047	0.045	0.047	0.047	0.045
0.10	0.046	0.120	0.045	0.070	0.115
0.20	0.114	0.226	0.115	0.152	0.203
0.30	0.210	0.324	0.203	0.246	0.286
0.40	0.328	0.430	0.286	0.348	0.420
0.50	0.442	0.525	0.419	0.462	0.520
0.60	0.530	0.623	0.519	0.557	0.628
0.70	0.623	0.722	0.627	0.657	0.717
0.80	0.727	0.816	0.717	0.753	0.824
0.90	0.815	0.919	0.824	0.853	0.923
1.00	0.922	1.050	0.923	0.965	1.009
1.10	1.049	1.153	1.009	1.070	1.167
1.20	1.159	1.318	1.166	1.214	1.322
1.20	1.314	1.309	1.322	1.315	1.302
1.20	1.306	1.300	1.302	1.303	1.301
1.20	1.289	1.303	1.301	1.298	1.298
1.20	1.297	1.301	1.298	1.299	1.300
1.20	1.297	1.294	1.300	1.297	1.296
1.20	1.299	1.304	1.296	1.300	1.305
1.10	1.294	1.172	1.305	1.257	1.178
1.00	1.175	1.056	1.178	1.136	1.051
0.90	1.059	0.946	1.051	1.019	0.925
0.80	0.929	0.811	0.925	0.889	0.831
0.70	0.857	0.720	0.832	0.803	0.728
0.60	0.727	0.619	0.728	0.691	0.632
0.50	0.632	0.527	0.632	0.597	0.530
0.40	0.532	0.438	0.530	0.500	0.434
0.30	0.432	0.344	0.435	0.404	0.345
0.20	0.341	0.225	0.345	0.304	0.224
0.10	0.211	0.114	0.224	0.183	0.135
0.00	0.128	0.048	0.135	0.104	0.050

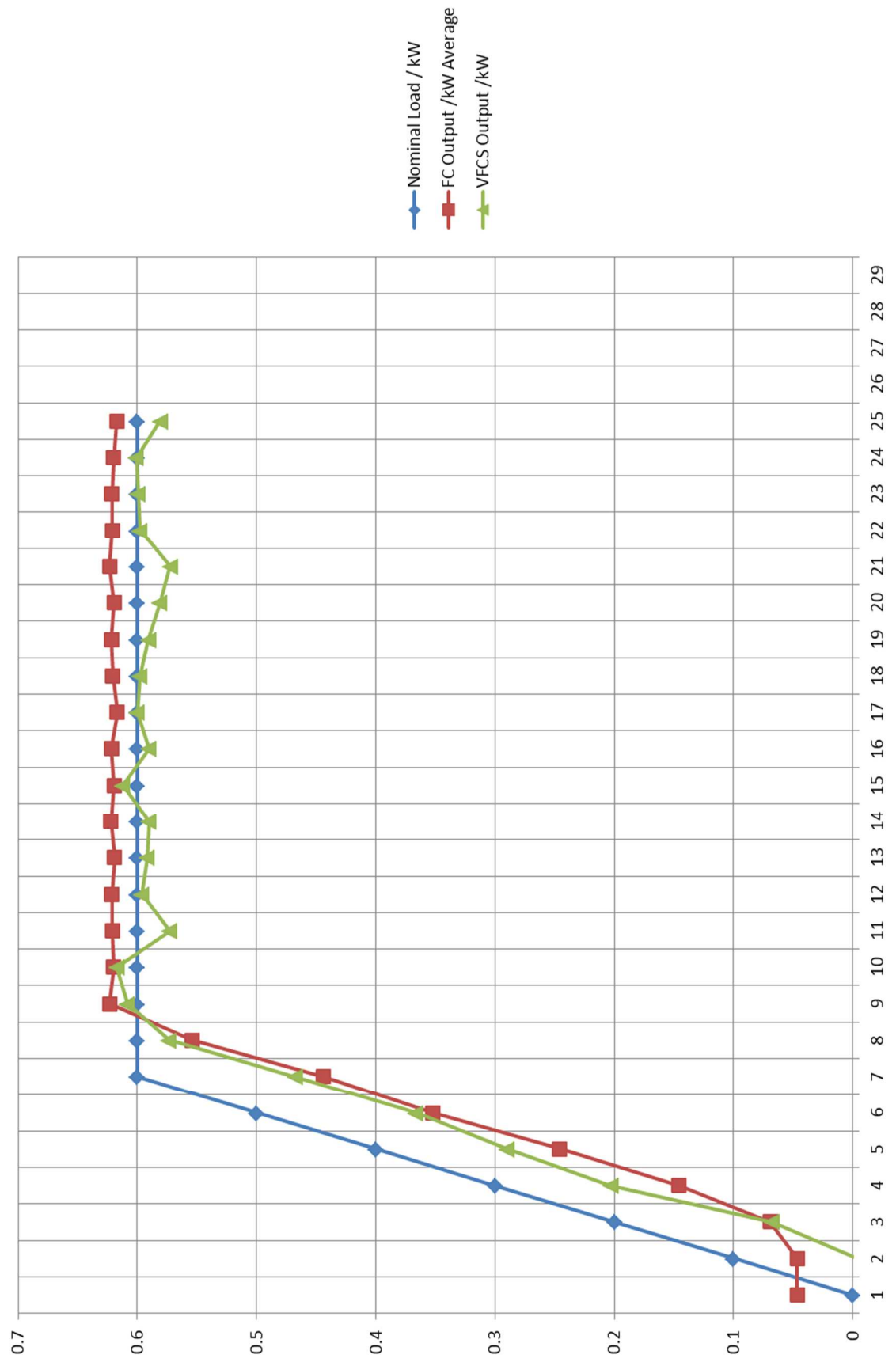


Appendix A-3. Load Profile 3

Profile 3 is ramped up to 0.6kW at the same rate as the previous profiles however the fuel cell is held at this peak power.

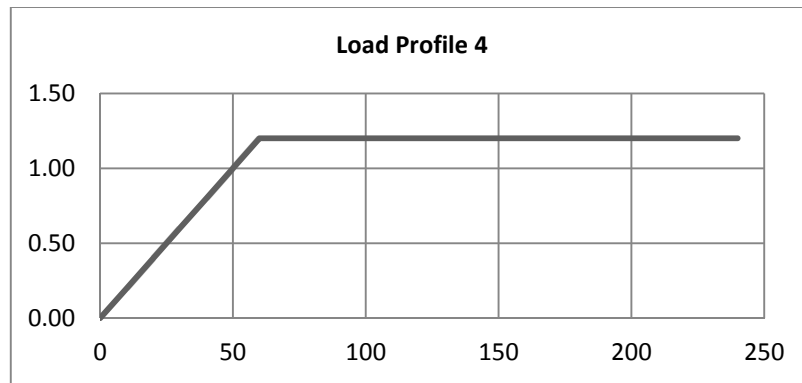


Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.042	0.057	0.041	0.047	-0.003
0.10	0.048	0.045	0.047	0.047	-0.003
0.20	0.046	0.116	0.046	0.069	0.068
0.30	0.115	0.193	0.129	0.146	0.203
0.40	0.207	0.323	0.207	0.246	0.290
0.50	0.332	0.394	0.330	0.352	0.366
0.60	0.389	0.520	0.423	0.444	0.468
0.60	0.527	0.622	0.513	0.554	0.574
0.60	0.627	0.621	0.622	0.623	0.608
0.60	0.617	0.621	0.621	0.620	0.617
0.60	0.615	0.627	0.621	0.621	0.573
0.60	0.619	0.621	0.624	0.621	0.597
0.60	0.617	0.618	0.623	0.619	0.592
0.60	0.617	0.622	0.627	0.622	0.590
0.60	0.619	0.622	0.617	0.620	0.612
0.60	0.620	0.615	0.629	0.622	0.590
0.60	0.613	0.617	0.620	0.617	0.600
0.60	0.621	0.618	0.623	0.621	0.598
0.60	0.622	0.623	0.621	0.622	0.591
0.60	0.623	0.621	0.615	0.619	0.581
0.60	0.621	0.626	0.623	0.623	0.572
0.60	0.621	0.618	0.624	0.621	0.598
0.60	0.622	0.625	0.617	0.621	0.599
0.60	0.619	0.618	0.623	0.620	0.601
0.60	0.613	0.619	0.619	0.617	0.581

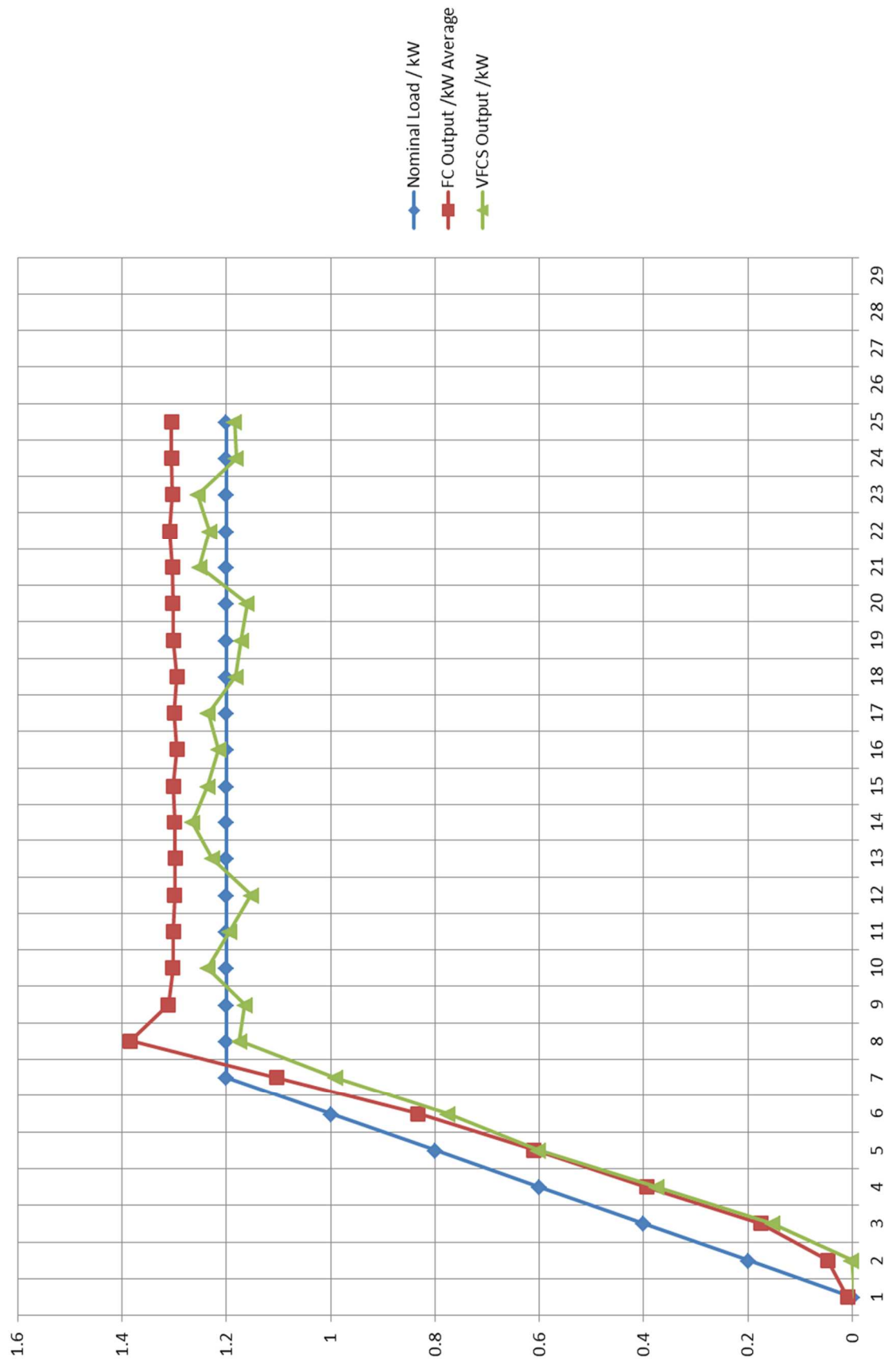


Appendix A-4. Load Profile 4

Profile 4 is ramped up to 1.2kW over 60s and held at this value.

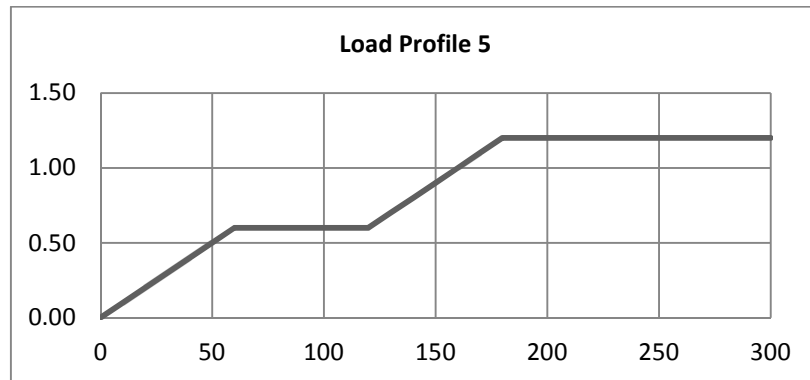


Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.008	0.010	0.009	0.009	-0.004
0.20	0.048	0.046	0.047	0.047	0.001
0.40	0.186	0.182	0.158	0.176	0.153
0.60	0.409	0.416	0.359	0.395	0.374
0.80	0.618	0.599	0.615	0.611	0.603
1.00	0.864	0.807	0.826	0.833	0.776
1.20	1.141	1.086	1.083	1.104	0.991
1.20	1.389	1.371	1.393	1.384	1.175
1.20	1.304	1.320	1.308	1.311	1.164
1.20	1.308	1.302	1.296	1.302	1.236
1.20	1.307	1.295	1.303	1.302	1.194
1.20	1.292	1.298	1.306	1.298	1.152
1.20	1.298	1.295	1.300	1.298	1.227
1.20	1.289	1.304	1.303	1.299	1.265
1.20	1.299	1.304	1.300	1.301	1.235
1.20	1.288	1.296	1.300	1.294	1.215
1.20	1.296	1.297	1.306	1.300	1.235
1.20	1.293	1.296	1.295	1.295	1.182
1.20	1.298	1.299	1.307	1.301	1.171
1.20	1.294	1.304	1.311	1.303	1.160
1.20	1.302	1.300	1.306	1.303	1.251
1.20	1.308	1.315	1.302	1.308	1.232
1.20	1.299	1.305	1.305	1.303	1.254
1.20	1.295	1.310	1.310	1.305	1.181
1.20	1.296	1.305	1.313	1.305	1.185

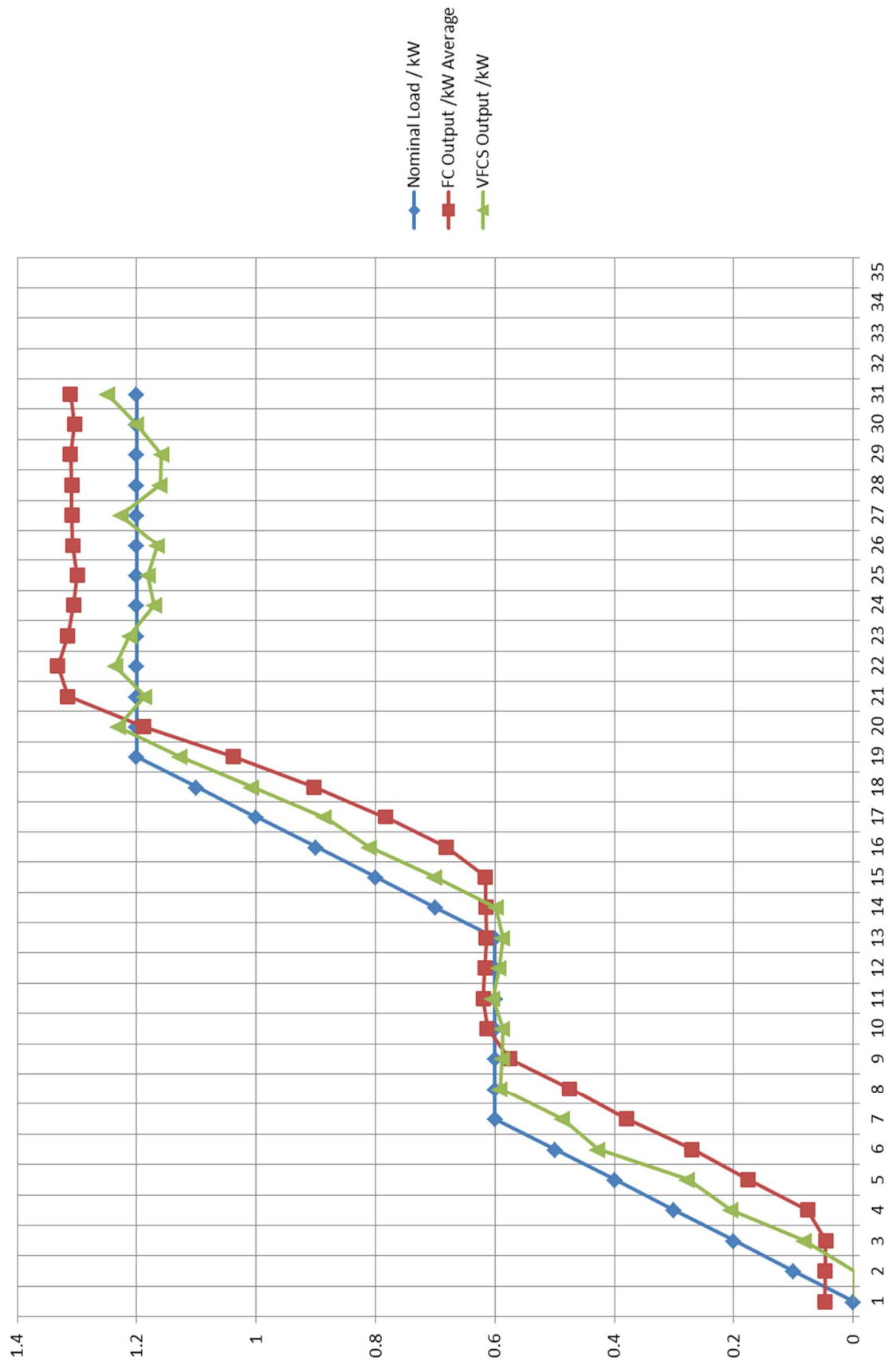


Appendix A-5. Load Profile 5

Profile 5 is ramped up to 1.2kW in stages. Once it reaches 0.6kW it is held for 60s before moving up to the full 1.2kW.

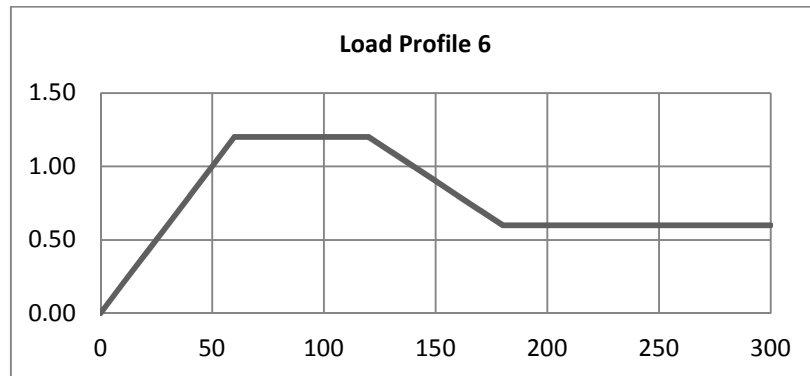


Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.053	0.042	0.047	0.047	-0.003
0.10	0.045	0.048	0.047	0.047	-0.002
0.20	0.046	0.046	0.047	0.046	0.082
0.30	0.046	0.086	0.096	0.076	0.205
0.40	0.095	0.243	0.192	0.177	0.277
0.50	0.199	0.330	0.281	0.270	0.428
0.60	0.298	0.419	0.421	0.379	0.487
0.60	0.392	0.520	0.513	0.475	0.592
0.60	0.513	0.608	0.604	0.575	0.588
0.60	0.604	0.614	0.621	0.613	0.587
0.60	0.622	0.620	0.617	0.620	0.603
0.60	0.616	0.616	0.617	0.617	0.593
0.60	0.616	0.612	0.615	0.614	0.587
0.70	0.617	0.612	0.616	0.615	0.599
0.80	0.617	0.613	0.617	0.616	0.701
0.90	0.618	0.712	0.715	0.682	0.811
1.00	0.704	0.823	0.824	0.784	0.886
1.10	0.820	0.950	0.940	0.903	1.007
1.20	0.947	1.082	1.083	1.038	1.127
1.20	1.095	1.256	1.213	1.188	1.231
1.20	1.228	1.363	1.355	1.316	1.187
1.20	1.363	1.313	1.321	1.332	1.236
1.20	1.322	1.312	1.313	1.316	1.211
1.20	1.307	1.302	1.307	1.305	1.170
1.20	1.300	1.304	1.297	1.300	1.181
1.20	1.302	1.308	1.312	1.307	1.165
1.20	1.305	1.305	1.316	1.309	1.227
1.20	1.310	1.307	1.310	1.309	1.160
1.20	1.314	1.312	1.307	1.311	1.158
1.20	1.299	1.310	1.303	1.304	1.200
1.20	1.303	1.316	1.313	1.311	1.249

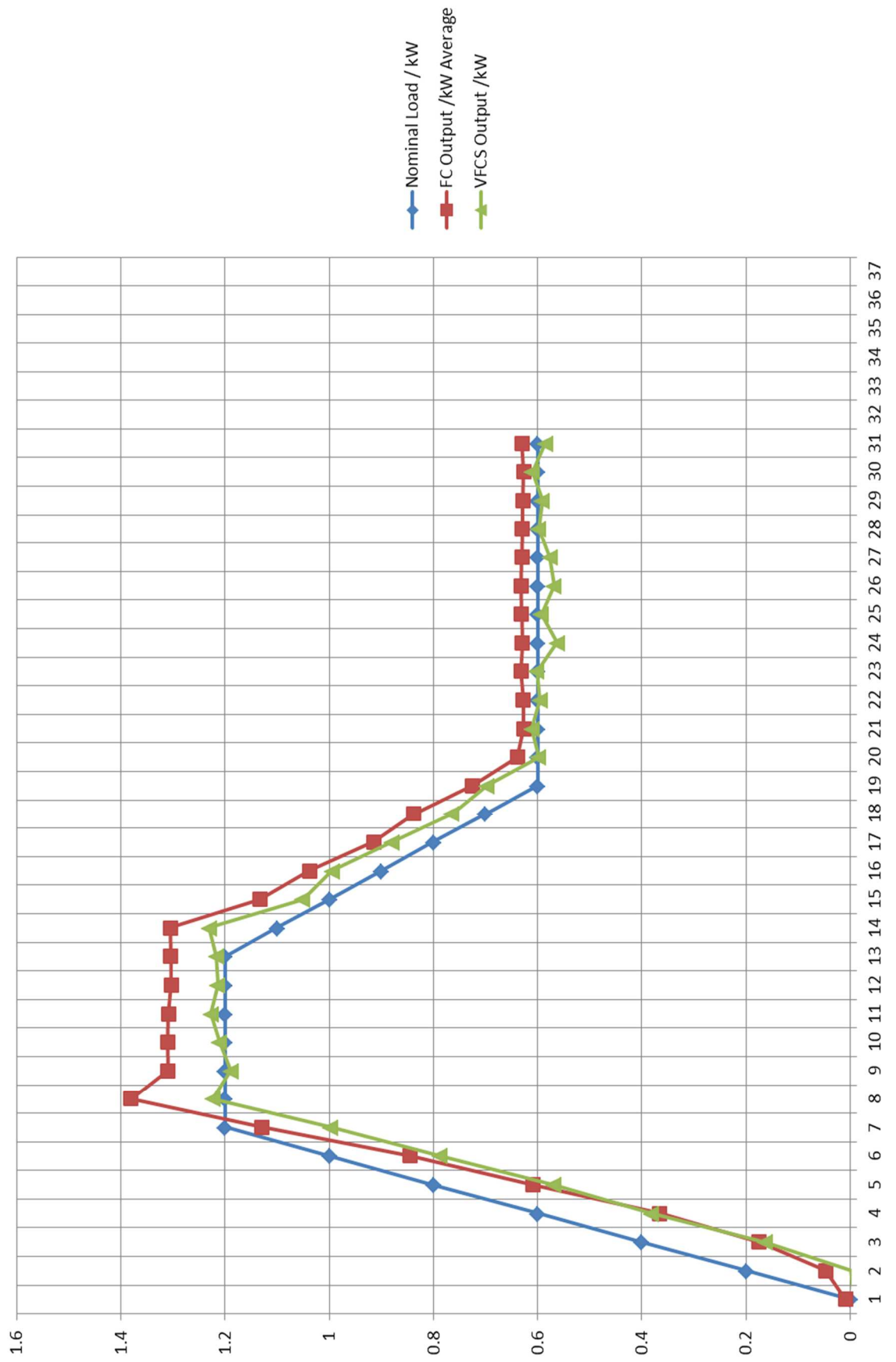


Appendix A-6. Load Profile 6

Profile 6 looks at the effect of reducing the load to 0.6kW once it has been held at 1.2kW.

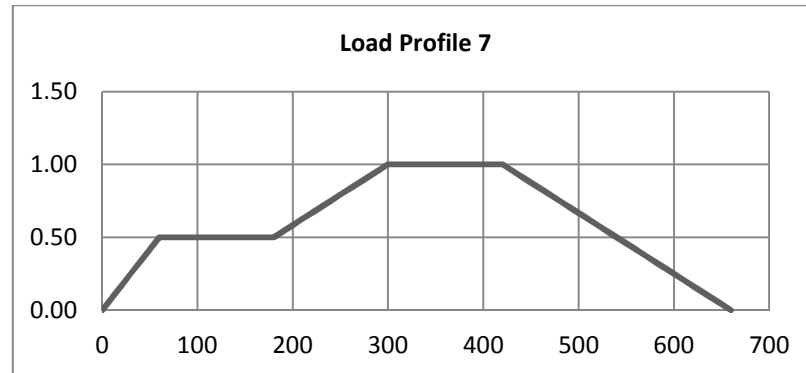


Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.008	0.009	0.010	0.009	-0.008
0.20	0.046	0.049	0.048	0.048	-0.001
0.40	0.182	0.173	0.169	0.175	0.163
0.60	0.360	0.373	0.364	0.366	0.382
0.80	0.594	0.612	0.619	0.608	0.569
1.00	0.842	0.834	0.859	0.845	0.787
1.20	1.116	1.109	1.164	1.130	0.998
1.20	1.373	1.383	1.385	1.381	1.224
1.20	1.312	1.317	1.300	1.310	1.189
1.20	1.310	1.310	1.310	1.310	1.211
1.20	1.316	1.296	1.314	1.309	1.227
1.20	1.303	1.301	1.305	1.303	1.213
1.20	1.316	1.295	1.301	1.304	1.216
1.10	1.311	1.295	1.310	1.305	1.230
1.00	1.128	1.141	1.131	1.133	1.051
0.90	1.039	1.046	1.029	1.038	0.995
0.80	0.911	0.916	0.917	0.915	0.879
0.70	0.821	0.855	0.836	0.837	0.764
0.60	0.726	0.725	0.724	0.725	0.697
0.60	0.643	0.641	0.633	0.639	0.598
0.60	0.633	0.622	0.624	0.626	0.611
0.60	0.628	0.621	0.633	0.627	0.596
0.60	0.633	0.632	0.631	0.632	0.602
0.60	0.629	0.629	0.629	0.629	0.563
0.60	0.628	0.630	0.634	0.631	0.592
0.60	0.632	0.633	0.632	0.632	0.569
0.60	0.629	0.633	0.629	0.630	0.576
0.60	0.628	0.632	0.628	0.629	0.598
0.60	0.627	0.629	0.628	0.628	0.591
0.60	0.626	0.630	0.625	0.627	0.610
0.60	0.627	0.631	0.632	0.630	0.585



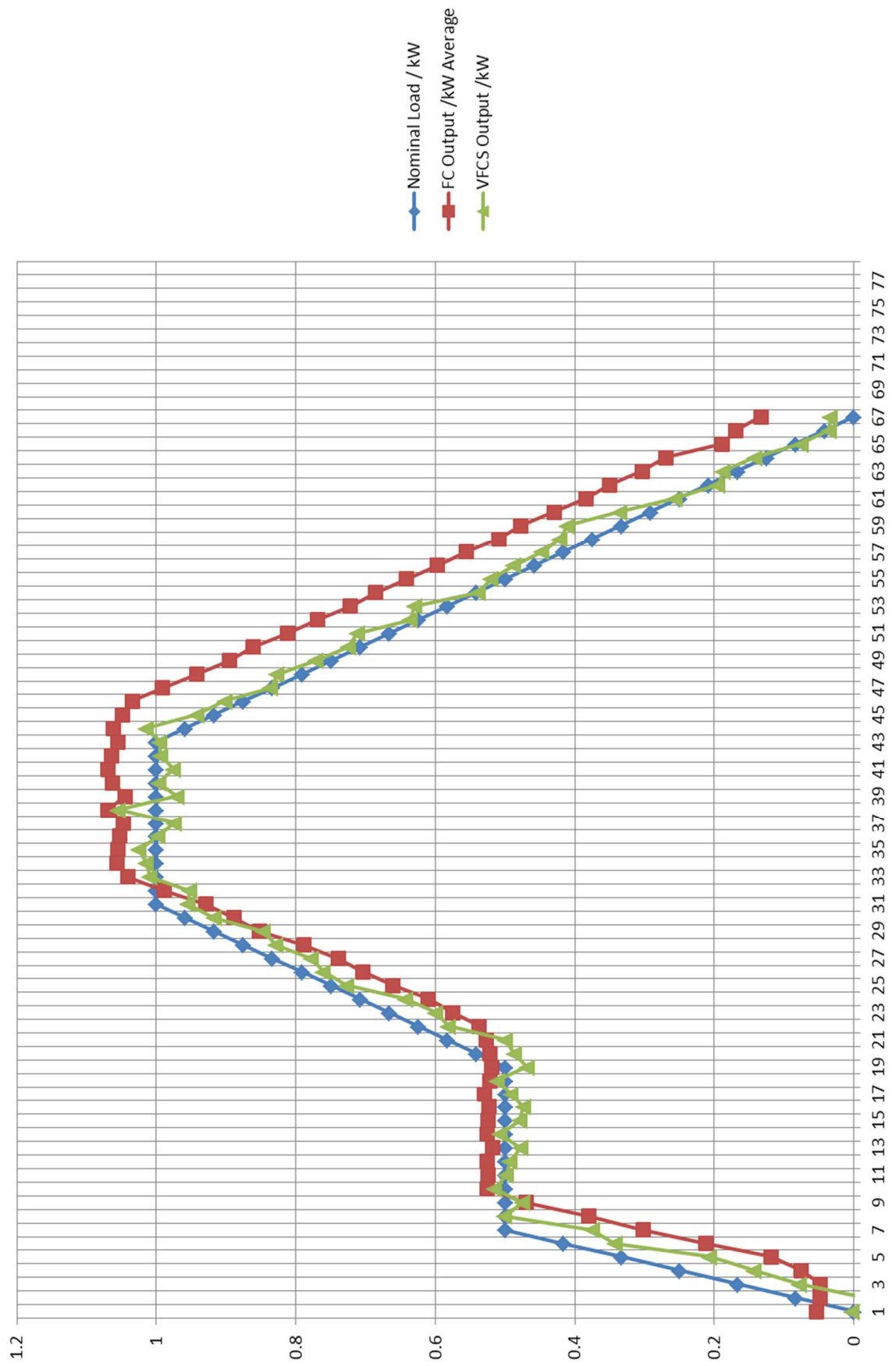
Appendix A-7. Load Profile 7

Profile 7 follows the load increase shown in Profile 5 however it peaks at 1kW instead of the maximum rated load (1.2kW). Profile 7 lasts 11 minutes and returns the load to 0kW.



Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.009	0.054	0.010	0.053	0.003
0.08	0.054	0.049	0.056	0.049	-0.015
0.17	0.050	0.048	0.048	0.048	0.079
0.25	0.048	0.047	0.049	0.076	0.143
0.33	0.048	0.132	0.048	0.118	0.207
0.42	0.081	0.178	0.097	0.212	0.342
0.50	0.183	0.260	0.193	0.302	0.375
0.50	0.287	0.345	0.274	0.380	0.501
0.50	0.361	0.419	0.358	0.470	0.475
0.50	0.443	0.517	0.450	0.525	0.515
0.50	0.526	0.525	0.524	0.524	0.499
0.50	0.522	0.523	0.527	0.526	0.493
0.50	0.526	0.524	0.527	0.518	0.478
0.50	0.507	0.524	0.523	0.525	0.507
0.50	0.522	0.528	0.525	0.525	0.479
0.50	0.522	0.525	0.527	0.523	0.474
0.50	0.523	0.527	0.520	0.529	0.491
0.50	0.531	0.528	0.529	0.522	0.512
0.50	0.526	0.520	0.519	0.519	0.468
0.54	0.519	0.521	0.519	0.522	0.487
0.58	0.521	0.525	0.519	0.527	0.500
0.63	0.527	0.523	0.530	0.537	0.581
0.67	0.519	0.563	0.529	0.575	0.600
0.71	0.560	0.593	0.573	0.610	0.643
0.75	0.595	0.640	0.595	0.661	0.728
0.79	0.645	0.696	0.643	0.704	0.761
0.83	0.674	0.747	0.693	0.739	0.778
0.88	0.712	0.766	0.740	0.789	0.828
0.92	0.771	0.828	0.766	0.852	0.846
0.96	0.829	0.895	0.832	0.889	0.918
1.00	0.876	0.907	0.885	0.929	0.954
1.00	0.909	0.965	0.913	0.989	0.953
1.00	0.967	1.028	0.972	1.041	1.009
1.00	1.017	1.066	1.039	1.056	1.015

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
1.00	1.052	1.065	1.051	1.055	1.025
1.00	1.052	1.065	1.051	1.055	1.025
1.00	1.043	1.065	1.057	1.052	0.998
1.00	1.028	1.063	1.065	1.047	0.974
1.00	1.025	1.077	1.039	1.069	1.055
1.00	1.062	1.087	1.059	1.045	0.971
1.00	1.034	1.047	1.055	1.063	0.997
1.00	1.065	1.068	1.056	1.070	0.975
1.00	1.080	1.074	1.055	1.064	0.994
1.00	1.060	1.071	1.060	1.056	0.995
0.96	1.049	1.077	1.042	1.062	1.014
0.92	1.067	1.065	1.054	1.048	0.942
0.88	1.061	1.030	1.055	1.035	0.902
0.83	1.071	1.004	1.029	0.991	0.836
0.79	1.011	0.957	1.005	0.942	0.827
0.75	0.957	0.912	0.956	0.895	0.772
0.71	0.910	0.876	0.900	0.861	0.725
0.67	0.871	0.833	0.880	0.812	0.712
0.63	0.828	0.783	0.825	0.769	0.636
0.58	0.776	0.750	0.781	0.722	0.630
0.54	0.727	0.705	0.732	0.685	0.539
0.50	0.703	0.654	0.699	0.641	0.520
0.46	0.653	0.615	0.656	0.597	0.488
0.42	0.607	0.578	0.605	0.556	0.448
0.38	0.560	0.530	0.578	0.509	0.421
0.33	0.529	0.475	0.523	0.477	0.411
0.29	0.505	0.441	0.486	0.429	0.336
0.25	0.446	0.406	0.436	0.383	0.256
0.21	0.400	0.361	0.390	0.350	0.195
0.17	0.358	0.331	0.360	0.303	0.187
0.13	0.313	0.294	0.303	0.270	0.142
0.08	0.283	0.230	0.296	0.188	0.076
0.04	0.192	0.181	0.192	0.169	0.036
0.00	0.180	0.147	0.179	0.169	0.033



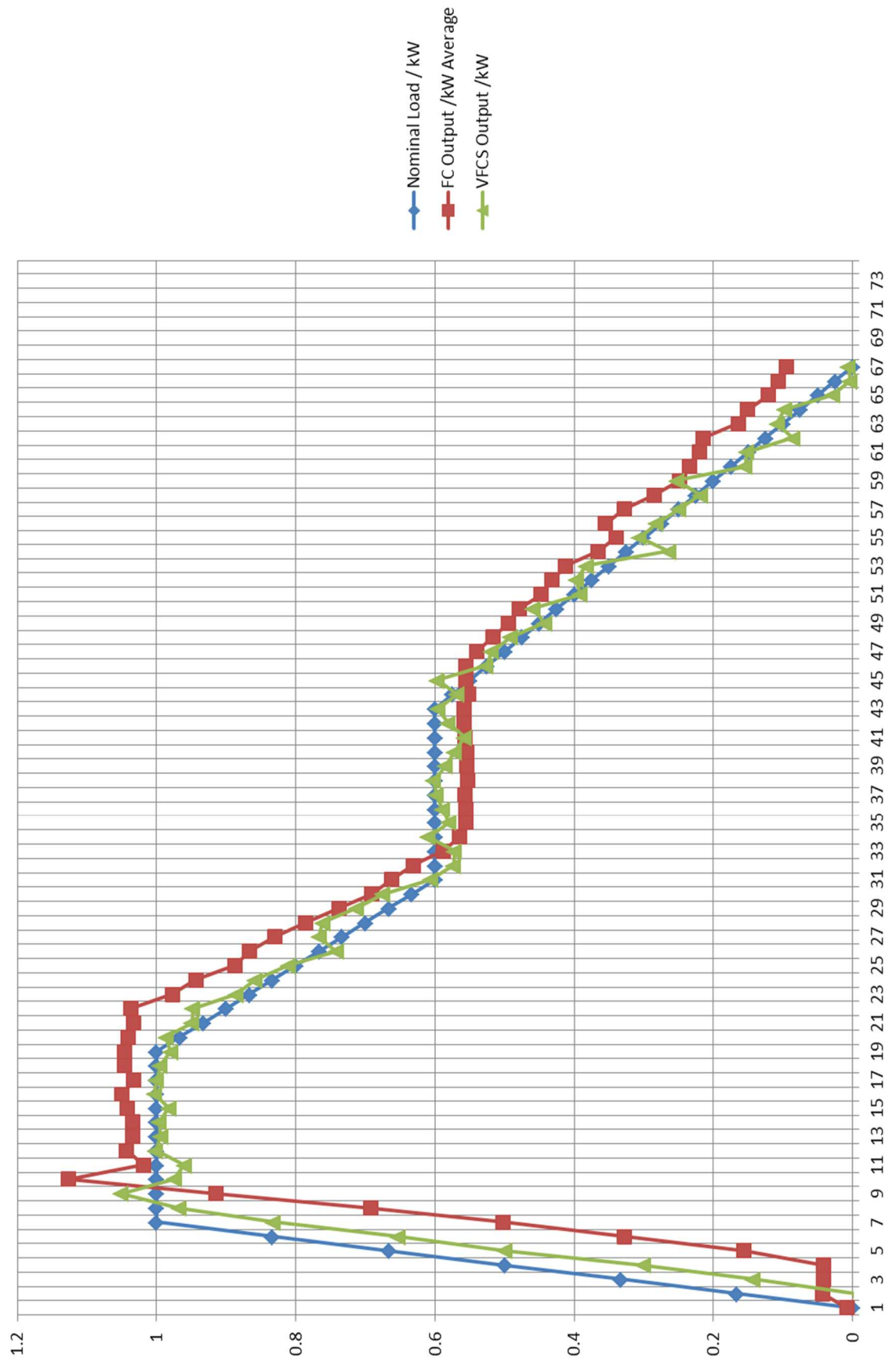
Appendix A-8. Load Profile 8

Profile 8 looks at quickly increasing the load to maximum and then reducing the load over an extended period of time.



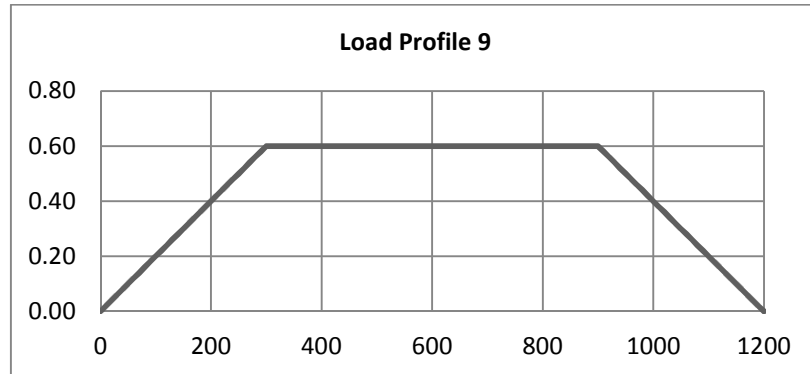
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.008	0.007	0.009	0.008	-0.007
0.17	0.052	0.037	0.041	0.043	-0.002
0.33	0.044	0.036	0.046	0.042	0.144
0.50	0.043	0.035	0.045	0.041	0.301
0.67	0.180	0.133	0.153	0.156	0.499
0.83	0.372	0.281	0.330	0.328	0.654
1.00	0.594	0.431	0.484	0.503	0.833
1.00	0.816	0.593	0.666	0.692	0.968
1.00	1.104	0.784	0.855	0.914	1.051
1.00	1.309	0.965	1.105	1.126	0.975
1.00	1.224	0.873	0.959	1.019	0.960
1.00	1.238	0.894	0.998	1.043	1.002
1.00	1.239	0.886	0.976	1.034	0.994
1.00	1.225	0.886	0.991	1.034	0.996
1.00	1.232	0.894	1.002	1.043	0.983
1.00	1.235	0.900	1.014	1.050	1.004
1.00	1.224	0.885	0.989	1.033	1.000
1.00	1.232	0.897	1.010	1.047	0.995
1.00	1.231	0.897	1.010	1.046	0.980
0.97	1.234	0.892	0.996	1.041	0.986
0.93	1.230	0.885	0.983	1.033	0.950
0.90	1.233	0.889	0.989	1.037	0.948
0.87	1.144	0.838	0.950	0.977	0.886
0.83	1.100	0.809	0.922	0.943	0.859
0.80	1.025	0.760	0.876	0.887	0.810
0.77	1.001	0.743	0.857	0.867	0.742
0.73	0.952	0.711	0.827	0.830	0.767
0.70	0.885	0.673	0.797	0.785	0.762
0.67	0.818	0.632	0.762	0.738	0.712
0.63	0.776	0.592	0.704	0.691	0.675
0.60	0.728	0.568	0.692	0.663	0.606
0.60	0.685	0.541	0.668	0.631	0.573
0.60	0.651	0.504	0.610	0.588	0.572
0.60	0.605	0.483	0.604	0.564	0.610
0.60	0.596	0.477	0.596	0.556	0.580
0.60	0.597	0.476	0.593	0.555	0.589

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.60	0.594	0.477	0.599	0.557	0.598
0.60	0.597	0.474	0.588	0.553	0.602
0.60	0.597	0.475	0.589	0.554	0.585
0.60	0.594	0.475	0.593	0.554	0.572
0.60	0.600	0.477	0.592	0.556	0.558
0.60	0.599	0.478	0.596	0.558	0.582
0.60	0.597	0.478	0.599	0.558	0.596
0.58	0.591	0.473	0.592	0.552	0.568
0.55	0.595	0.476	0.595	0.555	0.597
0.53	0.595	0.477	0.597	0.556	0.527
0.50	0.581	0.463	0.577	0.540	0.519
0.48	0.556	0.443	0.552	0.517	0.492
0.45	0.532	0.424	0.527	0.494	0.443
0.43	0.515	0.410	0.511	0.479	0.459
0.40	0.481	0.383	0.477	0.447	0.391
0.38	0.463	0.370	0.462	0.432	0.397
0.35	0.437	0.353	0.446	0.412	0.383
0.33	0.416	0.313	0.367	0.365	0.264
0.30	0.388	0.292	0.341	0.340	0.307
0.28	0.381	0.304	0.379	0.355	0.282
0.25	0.343	0.282	0.361	0.328	0.249
0.23	0.327	0.244	0.283	0.285	0.219
0.20	0.278	0.213	0.254	0.248	0.253
0.18	0.259	0.201	0.245	0.235	0.155
0.15	0.217	0.189	0.255	0.220	0.152
0.13	0.226	0.184	0.234	0.215	0.086
0.10	0.175	0.141	0.176	0.164	0.108
0.08	0.171	0.129	0.152	0.151	0.098
0.05	0.123	0.104	0.136	0.121	0.029
0.03	0.116	0.092	0.113	0.107	0.003
0.00	0.102	0.082	0.102	0.095	0.006



Appendix A-9. Load Profile 9

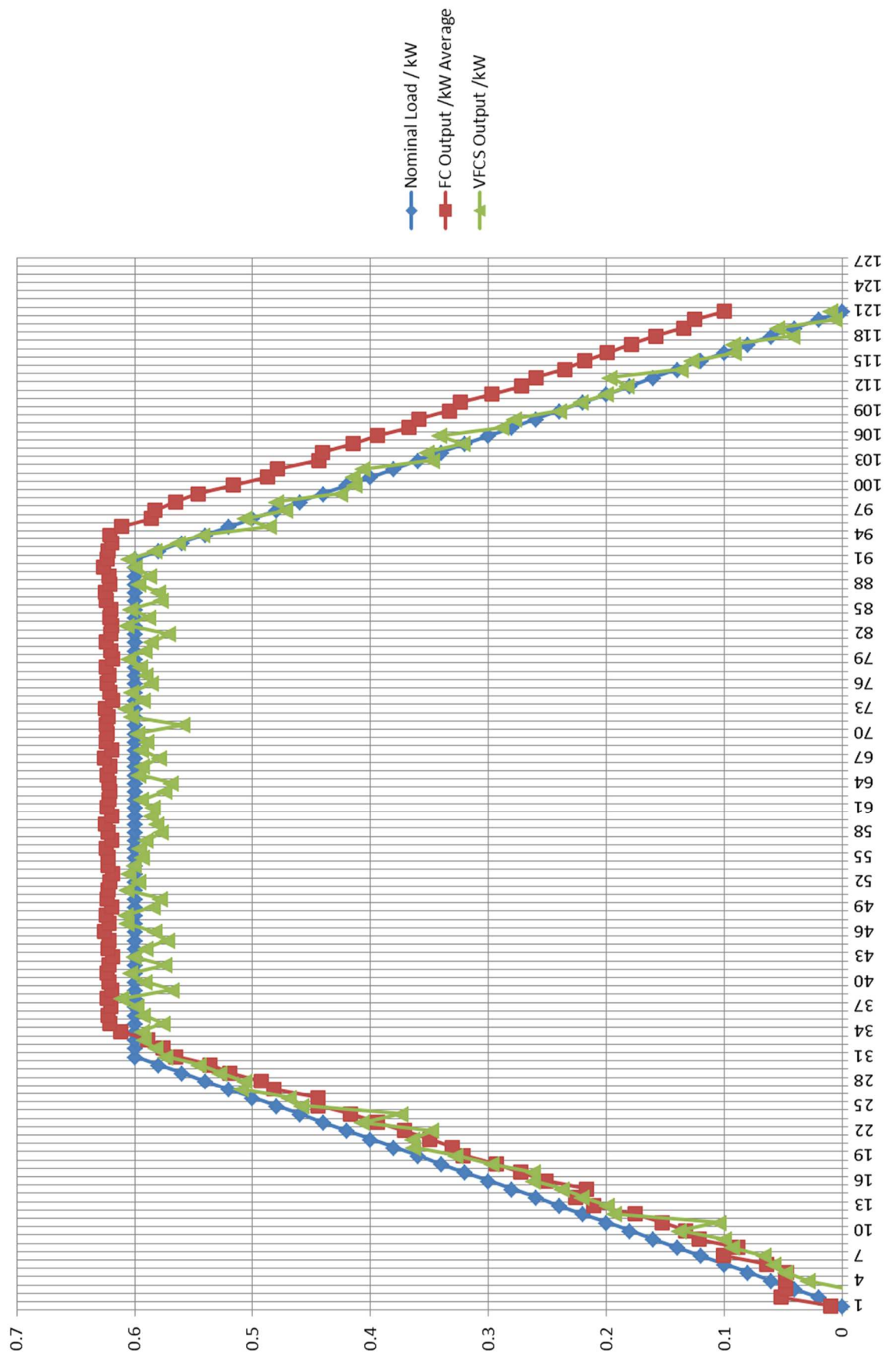
Profile 9 increases the fuel cell to 0.6kW over 5 minutes before holding it there for 10 minutes and then returning it back to 0W.



Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.010	0.009	0.010	0.010	-0.008
0.02	0.056	0.057	0.042	0.052	-0.002
0.04	0.048	0.049	0.047	0.048	-0.006
0.06	0.048	0.048	0.047	0.048	0.029
0.08	0.048	0.048	0.047	0.047	0.048
0.10	0.080	0.049	0.063	0.064	0.058
0.12	0.129	0.076	0.096	0.101	0.066
0.14	0.082	0.088	0.095	0.088	0.093
0.16	0.116	0.127	0.122	0.122	0.100
0.18	0.148	0.106	0.144	0.132	0.138
0.20	0.162	0.142	0.155	0.153	0.105
0.22	0.183	0.161	0.183	0.176	0.193
0.24	0.231	0.189	0.213	0.211	0.199
0.26	0.231	0.238	0.210	0.226	0.220
0.28	0.223	0.199	0.228	0.216	0.237
0.30	0.259	0.239	0.256	0.251	0.262
0.32	0.284	0.252	0.280	0.272	0.262
0.34	0.301	0.281	0.297	0.293	0.297
0.36	0.309	0.324	0.331	0.321	0.328
0.38	0.329	0.330	0.332	0.330	0.364
0.40	0.356	0.337	0.356	0.350	0.364
0.42	0.382	0.350	0.383	0.371	0.348
0.44	0.401	0.370	0.411	0.394	0.407
0.46	0.429	0.403	0.421	0.417	0.374
0.48	0.436	0.446	0.452	0.444	0.458
0.50	0.438	0.448	0.446	0.444	0.469
0.52	0.481	0.487	0.478	0.482	0.509
0.54	0.498	0.476	0.503	0.493	0.507
0.56	0.532	0.501	0.526	0.520	0.528
0.58	0.547	0.525	0.536	0.536	0.545
0.60	0.579	0.550	0.566	0.565	0.573
0.60	0.570	0.583	0.576	0.576	0.582
0.60	0.599	0.569	0.599	0.589	0.592
0.60	0.621	0.598	0.616	0.612	0.594
0.60	0.620	0.625	0.619	0.621	0.576
0.60	0.625	0.621	0.620	0.622	0.593

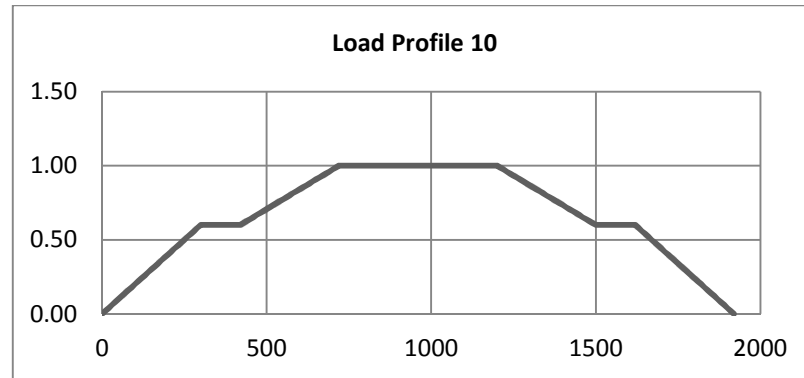
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.60	0.620	0.620	0.620	0.620	0.598
0.60	0.620	0.626	0.623	0.623	0.611
0.60	0.619	0.621	0.617	0.619	0.568
0.60	0.620	0.621	0.624	0.622	0.591
0.60	0.622	0.621	0.626	0.623	0.603
0.60	0.624	0.621	0.621	0.622	0.574
0.60	0.622	0.617	0.619	0.619	0.600
0.60	0.621	0.626	0.620	0.623	0.590
0.60	0.620	0.625	0.620	0.621	0.572
0.60	0.622	0.625	0.629	0.626	0.583
0.60	0.622	0.621	0.623	0.622	0.606
0.60	0.624	0.625	0.624	0.624	0.607
0.60	0.620	0.617	0.622	0.620	0.584
0.60	0.624	0.625	0.622	0.623	0.578
0.60	0.624	0.621	0.622	0.622	0.606
0.60	0.624	0.617	0.622	0.621	0.597
0.60	0.617	0.617	0.621	0.618	0.605
0.60	0.616	0.626	0.626	0.622	0.601
0.60	0.624	0.621	0.623	0.623	0.594
0.60	0.624	0.625	0.623	0.624	0.596
0.60	0.617	0.618	0.623	0.619	0.590
0.60	0.625	0.624	0.618	0.622	0.577
0.60	0.624	0.626	0.625	0.625	0.581
0.60	0.623	0.616	0.618	0.619	0.586
0.60	0.624	0.621	0.624	0.623	0.584
0.60	0.618	0.623	0.624	0.622	0.594
0.60	0.623	0.616	0.624	0.621	0.575
0.60	0.625	0.618	0.623	0.622	0.569
0.60	0.622	0.626	0.621	0.623	0.596
0.60	0.621	0.617	0.624	0.621	0.594
0.60	0.625	0.625	0.625	0.625	0.579
0.60	0.623	0.619	0.618	0.620	0.595
0.60	0.624	0.625	0.624	0.624	0.589
0.60	0.623	0.623	0.624	0.623	0.597
0.60	0.624	0.623	0.625	0.624	0.559
0.60	0.621	0.621	0.625	0.623	0.603
0.60	0.631	0.625	0.618	0.625	0.607
0.60	0.616	0.616	0.625	0.619	0.592
0.60	0.622	0.624	0.617	0.621	0.602
0.60	0.624	0.625	0.621	0.623	0.586
0.60	0.624	0.622	0.619	0.622	0.591
0.60	0.629	0.620	0.622	0.624	0.595
0.60	0.623	0.615	0.617	0.619	0.605
0.60	0.619	0.618	0.624	0.621	0.592
0.60	0.623	0.623	0.626	0.624	0.586
0.60	0.617	0.625	0.620	0.621	0.571
0.60	0.621	0.623	0.613	0.619	0.607
0.60	0.621	0.624	0.617	0.621	0.588
0.60	0.622	0.615	0.625	0.621	0.603
0.60	0.621	0.625	0.626	0.624	0.578
0.60	0.625	0.624	0.625	0.625	0.579
0.60	0.621	0.624	0.617	0.621	0.597
0.60	0.621	0.624	0.620	0.622	0.588
0.60	0.627	0.625	0.626	0.626	0.599
0.60	0.623	0.623	0.623	0.623	0.605
0.58	0.621	0.624	0.622	0.622	0.583

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.56	0.620	0.620	0.620	0.620	0.563
0.54	0.622	0.620	0.621	0.621	0.542
0.52	0.600	0.623	0.611	0.611	0.486
0.50	0.576	0.595	0.586	0.586	0.506
0.48	0.592	0.573	0.583	0.583	0.472
0.46	0.546	0.586	0.566	0.566	0.480
0.44	0.535	0.557	0.546	0.546	0.426
0.42	0.502	0.531	0.517	0.517	0.413
0.40	0.477	0.498	0.488	0.488	0.414
0.38	0.481	0.478	0.479	0.479	0.406
0.36	0.441	0.446	0.444	0.444	0.347
0.34	0.433	0.448	0.440	0.440	0.352
0.32	0.406	0.424	0.415	0.415	0.322
0.30	0.380	0.409	0.394	0.394	0.342
0.28	0.354	0.380	0.367	0.367	0.289
0.26	0.356	0.362	0.359	0.359	0.278
0.24	0.333	0.334	0.333	0.333	0.240
0.22	0.306	0.342	0.324	0.324	0.221
0.20	0.287	0.307	0.297	0.297	0.200
0.18	0.260	0.283	0.272	0.272	0.182
0.16	0.249	0.270	0.260	0.260	0.197
0.14	0.220	0.251	0.235	0.235	0.137
0.12	0.191	0.246	0.219	0.219	0.127
0.10	0.193	0.205	0.199	0.199	0.091
0.08	0.166	0.192	0.179	0.179	0.092
0.06	0.139	0.168	0.168	0.158	0.042
0.04	0.116	0.144	0.144	0.135	0.055
0.02	0.126	0.127	0.122	0.125	0.006
0.00	0.086	0.095	0.120	0.100	0.010



Appendix A-10. Load Profile 10

Profile 10 lasts for 32 minutes in total. The fuel cell is taken to 1kW and back down to 0 following a simple step pattern. The load reaches 1kw after 12 minutes.

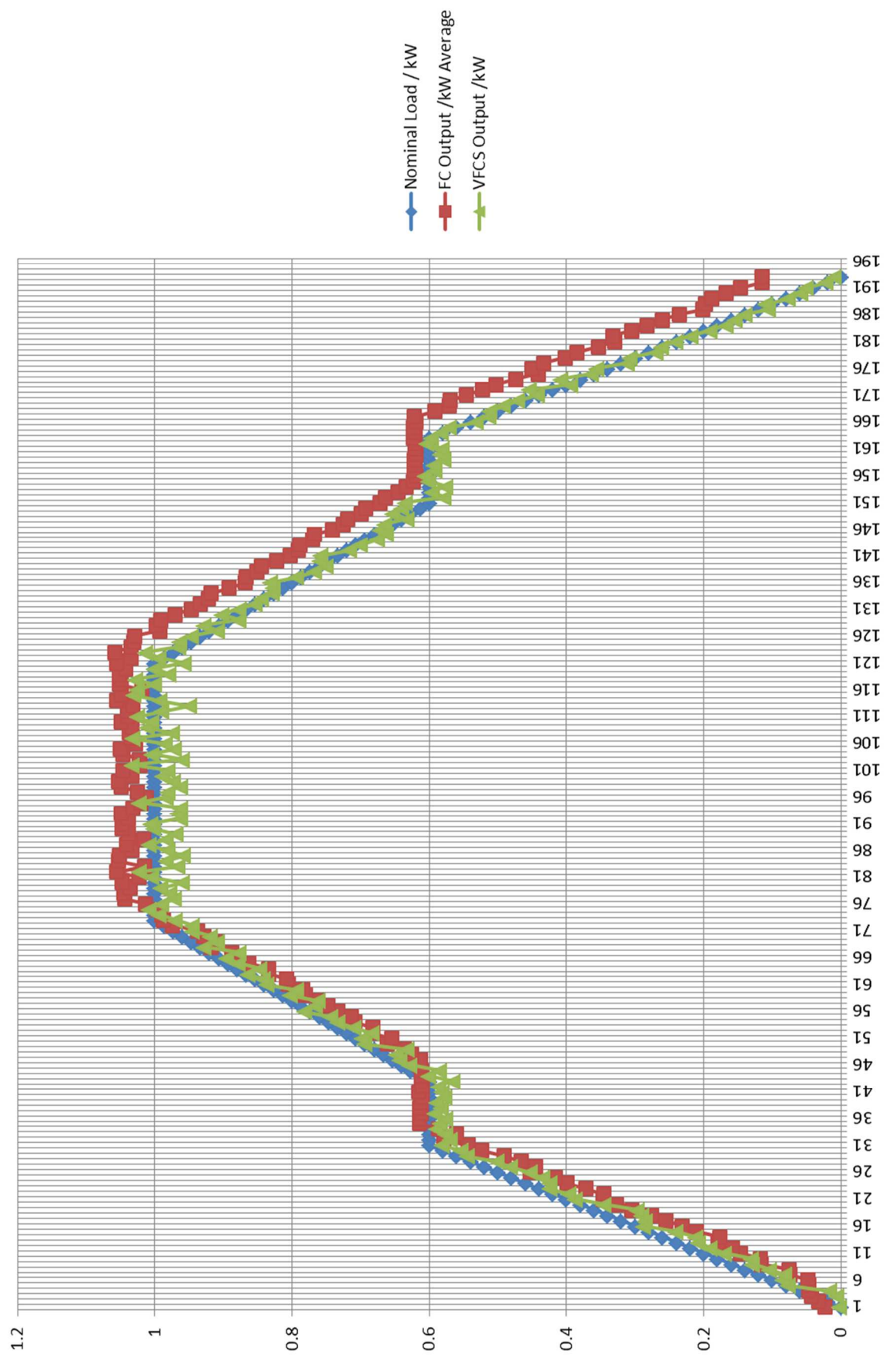


Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.007	0.042	0.021	0.012	0.002
0.02	0.010	0.058	0.027	0.023	-0.013
0.04	0.045	0.048	0.037	0.032	0.007
0.06	0.052	0.050	0.041	0.043	0.017
0.08	0.050	0.050	0.040	0.047	0.077
0.10	0.052	0.051	0.041	0.047	0.085
0.12	0.080	0.079	0.064	0.048	0.082
0.14	0.102	0.061	0.065	0.074	0.104
0.16	0.120	0.129	0.100	0.076	0.129
0.18	0.123	0.129	0.101	0.117	0.131
0.20	0.161	0.154	0.126	0.117	0.170
0.22	0.170	0.170	0.136	0.147	0.191
0.24	0.176	0.208	0.154	0.159	0.208
0.26	0.193	0.186	0.151	0.179	0.212
0.28	0.231	0.221	0.181	0.177	0.241
0.30	0.253	0.244	0.199	0.211	0.288
0.32	0.269	0.277	0.218	0.232	0.285
0.34	0.298	0.294	0.237	0.255	0.290
0.36	0.325	0.328	0.261	0.276	0.297
0.38	0.345	0.357	0.281	0.305	0.346
0.40	0.393	0.352	0.298	0.328	0.387
0.42	0.370	0.371	0.297	0.347	0.397
0.44	0.394	0.403	0.319	0.346	0.424
0.46	0.429	0.427	0.342	0.372	0.425
0.48	0.449	0.443	0.357	0.399	0.435
0.50	0.486	0.486	0.389	0.416	0.453
0.52	0.462	0.492	0.381	0.453	0.482
0.54	0.498	0.500	0.399	0.445	0.502
0.56	0.524	0.527	0.421	0.465	0.545
0.58	0.567	0.554	0.448	0.491	0.554
0.60	0.580	0.585	0.466	0.523	0.581
0.60	0.620	0.620	0.496	0.544	0.569
0.60	0.605	0.596	0.480	0.579	0.577
0.60	0.631	0.626	0.503	0.560	0.590

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.60	0.661	0.656	0.527	0.587	0.584
0.60	0.658	0.657	0.526	0.615	0.576
0.60	0.652	0.658	0.524	0.614	0.591
0.60	0.656	0.659	0.526	0.611	0.583
0.60	0.660	0.653	0.525	0.614	0.589
0.60	0.653	0.653	0.523	0.613	0.577
0.60	0.662	0.657	0.528	0.610	0.582
0.60	0.654	0.655	0.523	0.616	0.587
0.60	0.654	0.657	0.524	0.611	0.566
0.61	0.655	0.655	0.524	0.612	0.601
0.63	0.654	0.656	0.524	0.612	0.586
0.64	0.657	0.659	0.526	0.611	0.628
0.65	0.655	0.658	0.525	0.614	0.643
0.67	0.684	0.658	0.537	0.613	0.648
0.68	0.678	0.687	0.546	0.626	0.632
0.69	0.709	0.708	0.567	0.637	0.694
0.71	0.700	0.703	0.561	0.661	0.698
0.72	0.730	0.732	0.585	0.655	0.683
0.73	0.731	0.731	0.585	0.682	0.709
0.75	0.764	0.754	0.607	0.682	0.734
0.76	0.762	0.768	0.612	0.708	0.743
0.77	0.784	0.788	0.629	0.714	0.782
0.79	0.806	0.797	0.641	0.734	0.766
0.80	0.815	0.819	0.654	0.748	0.763
0.81	0.837	0.835	0.669	0.763	0.802
0.83	0.839	0.841	0.672	0.780	0.794
0.84	0.866	0.858	0.690	0.784	0.837
0.85	0.866	0.865	0.692	0.805	0.843
0.87	0.888	0.899	0.715	0.808	0.864
0.88	0.890	0.897	0.715	0.834	0.847
0.89	0.916	0.933	0.740	0.834	0.879
0.91	0.937	0.942	0.752	0.863	0.896
0.92	0.953	0.949	0.761	0.877	0.877
0.93	0.979	0.988	0.787	0.887	0.928
0.95	0.977	0.976	0.781	0.918	0.908
0.96	0.991	0.997	0.795	0.911	0.919
0.97	1.003	1.006	0.804	0.928	0.946
0.99	1.037	1.051	0.835	0.938	0.945
1.00	1.074	1.040	0.846	0.974	0.970
1.00	1.056	1.067	0.849	0.987	0.994
1.00	1.077	1.060	0.855	0.991	1.009
1.00	1.087	1.085	0.869	0.997	0.989
1.00	1.115	1.122	0.895	1.014	0.971
1.00	1.099	1.139	0.895	1.044	0.978
1.00	1.115	1.106	0.888	1.045	0.992
1.00	1.141	1.105	0.898	1.036	0.960
1.00	1.078	1.115	0.877	1.048	1.005
1.00	1.137	1.124	0.905	1.023	1.023
1.00	1.090	1.085	0.870	1.055	0.966
1.00	1.131	1.125	0.902	1.015	0.984
1.00	1.126	1.127	0.901	1.053	0.958
1.00	1.133	1.083	0.886	1.052	0.981
1.00	1.101	1.129	0.892	1.034	1.008
1.00	1.084	1.093	0.871	1.041	0.983
1.00	1.121	1.104	0.890	1.016	0.969
1.00	1.112	1.135	0.898	1.038	1.001

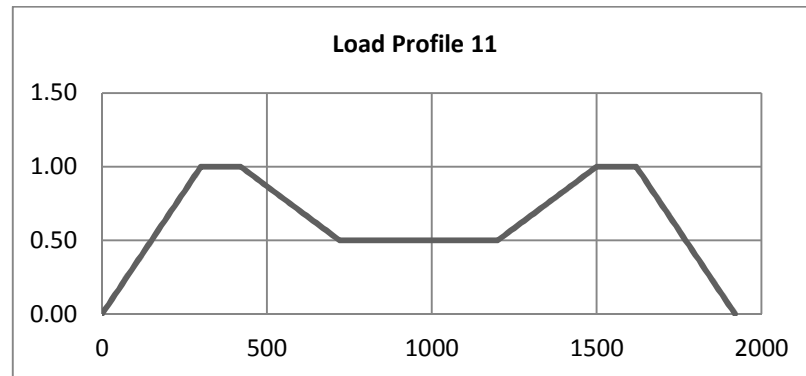
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
1.00	1.126	1.120	0.898	1.048	1.005
1.00	1.131	1.094	0.890	1.048	0.963
1.00	1.128	1.121	0.899	1.038	0.966
1.00	1.090	1.120	0.884	1.049	0.963
1.00	1.092	1.092	0.874	1.031	1.022
1.00	1.102	1.068	0.868	1.019	0.983
1.00	1.103	1.094	0.879	1.013	0.981
1.00	1.126	1.123	0.899	1.026	0.963
1.00	1.131	1.126	0.902	1.049	0.973
1.00	1.092	1.122	0.885	1.053	0.989
1.00	1.133	1.109	0.897	1.033	0.981
1.00	1.095	1.093	0.875	1.046	1.033
1.00	1.084	1.106	0.876	1.021	0.960
1.00	1.117	1.124	0.897	1.022	1.005
1.00	1.113	1.138	0.900	1.046	0.972
1.00	1.126	1.078	0.881	1.051	0.984
1.00	1.096	1.120	0.886	1.028	1.032
1.00	1.112	1.111	0.889	1.034	0.974
1.00	1.127	1.088	0.886	1.037	1.010
1.00	1.114	1.134	0.899	1.034	1.005
1.00	1.121	1.106	0.891	1.049	1.025
1.00	1.101	1.126	0.891	1.039	0.989
1.00	1.097	1.114	0.884	1.039	0.950
1.00	1.128	1.134	0.905	1.032	0.993
1.00	1.110	1.137	0.899	1.056	1.031
1.00	1.097	1.087	0.873	1.049	1.025
1.00	1.114	1.138	0.901	1.019	1.001
1.00	1.113	1.136	0.900	1.051	1.028
1.00	1.134	1.120	0.901	1.049	0.980
1.00	1.127	1.107	0.894	1.052	1.000
1.00	1.119	1.144	0.905	1.042	0.957
0.99	1.099	1.118	0.887	1.056	0.994
0.97	1.136	1.131	0.907	1.035	1.013
0.96	1.125	1.092	0.887	1.058	0.965
0.95	1.093	1.116	0.884	1.034	0.964
0.93	1.095	1.110	0.882	1.031	0.946
0.92	1.066	1.062	0.851	1.029	0.908
0.91	1.067	1.072	0.856	0.993	0.929
0.89	1.044	1.081	0.850	0.998	0.877
0.88	1.038	1.040	0.831	0.992	0.902
0.87	1.009	1.019	0.811	0.970	0.878
0.85	0.994	1.007	0.801	0.946	0.854
0.84	0.990	0.985	0.790	0.934	0.844
0.83	0.977	0.989	0.787	0.922	0.829
0.81	0.948	0.962	0.764	0.918	0.827
0.80	0.935	0.924	0.744	0.892	0.832
0.79	0.926	0.932	0.743	0.868	0.793
0.77	0.896	0.928	0.730	0.867	0.767
0.76	0.903	0.906	0.724	0.851	0.750
0.75	0.884	0.877	0.704	0.844	0.760
0.73	0.844	0.875	0.688	0.822	0.758
0.72	0.845	0.849	0.678	0.802	0.716
0.71	0.845	0.844	0.676	0.791	0.700
0.69	0.826	0.825	0.660	0.788	0.676
0.68	0.827	0.818	0.658	0.770	0.663
0.67	0.795	0.793	0.635	0.768	0.672

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.65	0.791	0.763	0.622	0.741	0.665
0.64	0.765	0.774	0.616	0.725	0.632
0.63	0.747	0.751	0.599	0.719	0.653
0.61	0.740	0.745	0.594	0.699	0.640
0.60	0.723	0.717	0.576	0.693	0.636
0.60	0.708	0.715	0.569	0.672	0.578
0.60	0.689	0.693	0.553	0.664	0.596
0.60	0.703	0.656	0.544	0.645	0.576
0.60	0.670	0.666	0.534	0.634	0.602
0.60	0.663	0.663	0.530	0.623	0.606
0.60	0.668	0.665	0.533	0.619	0.592
0.60	0.664	0.665	0.531	0.622	0.593
0.60	0.664	0.669	0.533	0.620	0.579
0.60	0.663	0.665	0.531	0.622	0.584
0.60	0.662	0.668	0.532	0.620	0.581
0.60	0.663	0.666	0.532	0.620	0.603
0.60	0.668	0.666	0.534	0.620	0.597
0.58	0.662	0.668	0.532	0.623	0.583
0.56	0.667	0.669	0.534	0.621	0.571
0.54	0.660	0.668	0.531	0.623	0.531
0.52	0.665	0.668	0.534	0.620	0.514
0.50	0.629	0.638	0.507	0.622	0.512
0.48	0.610	0.614	0.490	0.591	0.492
0.46	0.615	0.607	0.489	0.571	0.471
0.44	0.582	0.588	0.468	0.570	0.443
0.42	0.557	0.563	0.448	0.546	0.455
0.40	0.536	0.540	0.431	0.523	0.394
0.38	0.515	0.502	0.407	0.503	0.409
0.36	0.487	0.460	0.379	0.474	0.364
0.34	0.496	0.468	0.385	0.442	0.356
0.32	0.455	0.475	0.372	0.450	0.311
0.30	0.434	0.427	0.344	0.434	0.307
0.28	0.419	0.405	0.330	0.401	0.270
0.26	0.378	0.378	0.303	0.384	0.261
0.24	0.351	0.357	0.283	0.353	0.241
0.22	0.358	0.356	0.285	0.330	0.219
0.20	0.326	0.329	0.262	0.333	0.191
0.18	0.307	0.297	0.242	0.306	0.167
0.16	0.276	0.283	0.223	0.282	0.154
0.14	0.250	0.255	0.202	0.261	0.140
0.12	0.200	0.230	0.172	0.235	0.105
0.10	0.199	0.225	0.170	0.201	0.109
0.08	0.204	0.198	0.161	0.198	0.077
0.06	0.179	0.179	0.143	0.188	0.058
0.04	0.161	0.153	0.126	0.167	0.050
0.02	0.122	0.125	0.099	0.147	0.022
0.00	0.122	0.125	0.099	0.115	0.010



Appendix A-11. Load Profile 11

Profile 11 also lasts for 32 minutes however the load peaks are inverted from profile 10.

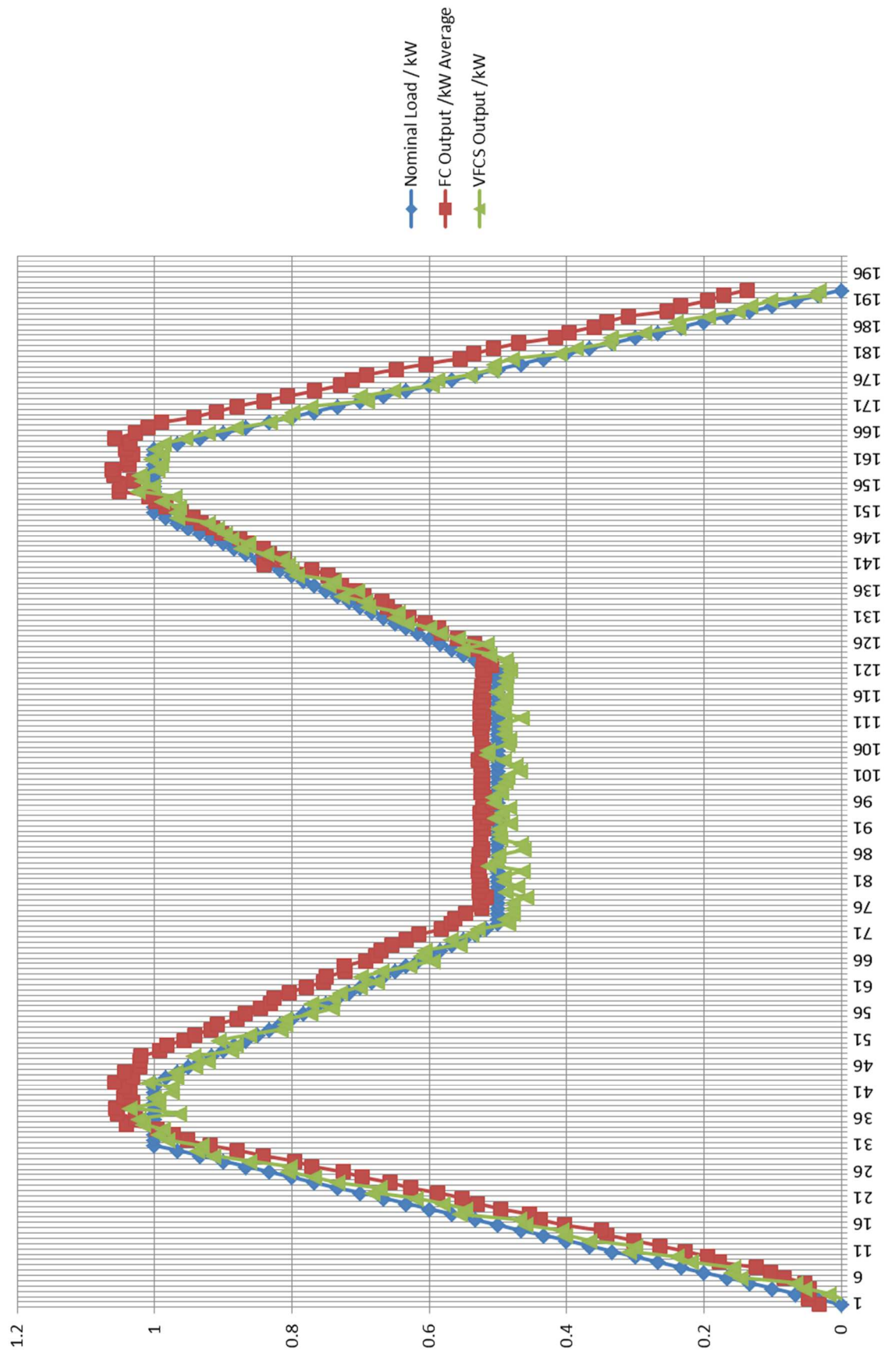


Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.009	0.056	0.031	0.032	-0.012
0.03	0.052	0.047	0.047	0.049	0.000
0.07	0.049	0.048	0.046	0.048	0.018
0.10	0.046	0.048	0.045	0.046	0.053
0.13	0.046	0.062	0.051	0.053	0.066
0.17	0.076	0.094	0.081	0.084	0.147
0.20	0.094	0.115	0.099	0.103	0.159
0.23	0.121	0.131	0.120	0.124	0.158
0.27	0.171	0.191	0.172	0.178	0.218
0.30	0.184	0.212	0.188	0.195	0.240
0.33	0.209	0.253	0.219	0.227	0.309
0.37	0.252	0.286	0.256	0.265	0.300
0.40	0.287	0.329	0.293	0.303	0.367
0.43	0.338	0.357	0.330	0.341	0.402
0.47	0.353	0.359	0.338	0.350	0.407
0.50	0.393	0.427	0.390	0.403	0.459
0.53	0.439	0.453	0.424	0.439	0.469
0.57	0.454	0.468	0.438	0.454	0.555
0.60	0.481	0.529	0.479	0.496	0.547
0.63	0.527	0.552	0.512	0.530	0.580
0.67	0.543	0.580	0.534	0.552	0.620
0.70	0.569	0.627	0.568	0.588	0.682
0.73	0.624	0.653	0.606	0.628	0.671
0.77	0.648	0.688	0.634	0.657	0.734
0.80	0.693	0.726	0.674	0.698	0.768
0.83	0.727	0.749	0.701	0.726	0.805
0.87	0.770	0.798	0.745	0.771	0.803
0.90	0.793	0.827	0.770	0.797	0.861
0.93	0.833	0.881	0.814	0.842	0.914
0.97	0.878	0.911	0.850	0.879	0.938
1.00	0.919	0.951	0.888	0.919	0.932
1.00	0.928	1.009	0.920	0.952	0.981
1.00	0.979	0.999	0.940	0.973	0.994
1.00	1.004	1.024	0.963	0.997	0.988
1.00	1.048	1.071	1.006	1.042	1.017
1.00	1.050	1.041	0.994	1.028	1.023

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
1.00	1.060	1.085	1.019	1.054	0.964
1.00	1.079	1.069	1.020	1.056	1.036
1.00	1.079	1.020	0.997	1.032	0.994
1.00	1.033	1.092	1.009	1.045	1.000
1.00	1.028	1.078	1.000	1.035	0.974
1.00	1.060	1.064	1.008	1.044	0.975
1.00	1.066	1.085	1.022	1.058	1.009
0.98	1.036	1.062	0.997	1.032	0.968
0.97	1.048	1.074	1.008	1.043	0.969
0.95	1.049	1.028	0.987	1.021	0.940
0.93	1.050	1.026	0.986	1.021	0.921
0.92	1.049	1.026	0.985	1.020	0.943
0.90	1.014	1.005	0.959	0.992	0.888
0.88	1.029	0.969	0.949	0.983	0.882
0.87	0.990	0.958	0.925	0.958	0.906
0.85	0.964	0.950	0.909	0.941	0.861
0.83	0.937	0.930	0.887	0.918	0.816
0.82	0.937	0.910	0.877	0.908	0.809
0.80	0.909	0.881	0.850	0.880	0.810
0.78	0.888	0.877	0.838	0.868	0.772
0.77	0.867	0.854	0.818	0.846	0.741
0.75	0.855	0.837	0.804	0.832	0.772
0.73	0.848	0.832	0.798	0.826	0.740
0.72	0.827	0.808	0.777	0.804	0.729
0.70	0.806	0.778	0.752	0.778	0.701
0.68	0.776	0.759	0.729	0.755	0.676
0.67	0.773	0.754	0.725	0.751	0.700
0.65	0.744	0.725	0.698	0.722	0.669
0.63	0.758	0.716	0.700	0.725	0.629
0.62	0.719	0.691	0.670	0.693	0.595
0.60	0.702	0.676	0.655	0.678	0.611
0.58	0.681	0.681	0.647	0.670	0.606
0.57	0.676	0.655	0.632	0.655	0.555
0.55	0.659	0.631	0.613	0.634	0.569
0.53	0.633	0.620	0.595	0.616	0.539
0.52	0.614	0.569	0.562	0.582	0.529
0.50	0.577	0.579	0.549	0.568	0.485
0.50	0.583	0.562	0.544	0.563	0.489
0.50	0.554	0.560	0.529	0.548	0.478
0.50	0.537	0.529	0.506	0.524	0.478
0.50	0.527	0.544	0.509	0.527	0.478
0.50	0.525	0.526	0.499	0.517	0.459
0.50	0.534	0.539	0.510	0.528	0.489
0.50	0.527	0.539	0.506	0.524	0.471
0.50	0.530	0.540	0.508	0.526	0.491
0.50	0.535	0.538	0.510	0.527	0.491
0.50	0.532	0.543	0.510	0.528	0.463
0.50	0.536	0.537	0.510	0.528	0.514
0.50	0.535	0.535	0.508	0.526	0.501
0.50	0.536	0.536	0.509	0.527	0.499
0.50	0.538	0.524	0.504	0.522	0.463
0.50	0.532	0.535	0.507	0.525	0.466
0.50	0.533	0.534	0.507	0.525	0.497
0.50	0.533	0.535	0.507	0.525	0.498
0.50	0.536	0.525	0.504	0.522	0.499
0.50	0.533	0.534	0.507	0.525	0.482

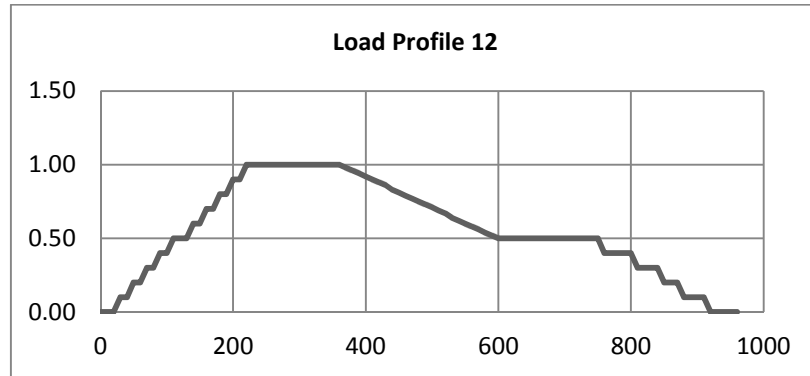
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.50	0.532	0.518	0.499	0.516	0.504
0.50	0.532	0.537	0.508	0.526	0.494
0.50	0.531	0.533	0.505	0.523	0.483
0.50	0.515	0.518	0.491	0.508	0.505
0.50	0.531	0.526	0.502	0.520	0.506
0.50	0.537	0.531	0.507	0.525	0.494
0.50	0.531	0.531	0.504	0.522	0.497
0.50	0.538	0.531	0.508	0.525	0.488
0.50	0.530	0.531	0.504	0.522	0.486
0.50	0.531	0.536	0.507	0.524	0.468
0.50	0.536	0.530	0.507	0.524	0.474
0.50	0.541	0.535	0.511	0.529	0.491
0.50	0.529	0.537	0.506	0.524	0.516
0.50	0.530	0.529	0.503	0.521	0.515
0.50	0.534	0.530	0.505	0.523	0.485
0.50	0.529	0.536	0.506	0.524	0.484
0.50	0.536	0.529	0.506	0.524	0.491
0.50	0.533	0.536	0.508	0.526	0.490
0.50	0.532	0.530	0.505	0.522	0.490
0.50	0.533	0.528	0.504	0.522	0.465
0.50	0.536	0.536	0.509	0.527	0.490
0.50	0.536	0.535	0.509	0.526	0.500
0.50	0.526	0.534	0.503	0.521	0.492
0.50	0.534	0.535	0.508	0.526	0.488
0.50	0.526	0.534	0.503	0.521	0.501
0.50	0.531	0.535	0.506	0.524	0.488
0.50	0.532	0.529	0.504	0.521	0.490
0.50	0.529	0.527	0.502	0.519	0.486
0.50	0.535	0.528	0.505	0.523	0.482
0.52	0.507	0.528	0.492	0.509	0.487
0.53	0.524	0.534	0.503	0.521	0.489
0.55	0.526	0.534	0.504	0.521	0.512
0.57	0.533	0.556	0.517	0.536	0.552
0.58	0.530	0.556	0.516	0.534	0.516
0.60	0.551	0.585	0.540	0.559	0.557
0.62	0.584	0.601	0.563	0.583	0.584
0.63	0.589	0.605	0.567	0.587	0.599
0.65	0.605	0.629	0.586	0.607	0.632
0.67	0.629	0.653	0.609	0.630	0.650
0.68	0.652	0.673	0.629	0.651	0.646
0.70	0.669	0.674	0.638	0.661	0.689
0.72	0.673	0.688	0.646	0.669	0.692
0.73	0.693	0.721	0.671	0.695	0.726
0.75	0.710	0.730	0.684	0.708	0.704
0.77	0.731	0.751	0.704	0.728	0.746
0.78	0.751	0.755	0.715	0.740	0.739
0.80	0.749	0.772	0.722	0.748	0.792
0.82	0.770	0.800	0.746	0.772	0.800
0.83	0.796	0.915	0.813	0.841	0.805
0.85	0.819	0.832	0.784	0.812	0.813
0.87	0.846	0.848	0.805	0.833	0.837
0.88	0.848	0.863	0.813	0.841	0.873
0.90	0.884	0.873	0.835	0.864	0.862
0.92	0.887	0.893	0.846	0.875	0.888
0.93	0.908	0.928	0.872	0.903	0.896
0.95	0.932	0.930	0.885	0.916	0.909

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.97	0.941	0.956	0.901	0.932	0.922
0.98	0.949	0.971	0.912	0.944	0.966
1.00	0.970	0.984	0.928	0.961	0.967
1.00	0.993	1.007	0.950	0.983	0.963
1.00	0.998	1.031	0.964	0.998	0.989
1.00	1.025	1.026	0.974	1.008	0.971
1.00	1.075	1.063	1.016	1.051	1.025
1.00	1.062	1.074	1.015	1.050	1.002
1.00	1.032	1.063	0.995	1.030	1.018
1.00	1.072	1.082	1.023	1.059	1.022
1.00	1.092	1.069	1.026	1.062	0.995
1.00	1.028	1.081	1.002	1.037	0.990
1.00	1.067	1.047	1.004	1.040	1.005
1.00	1.074	1.026	0.997	1.032	0.988
1.00	1.047	1.074	1.007	1.043	0.998
0.97	1.074	1.033	1.001	1.036	0.986
0.93	1.086	1.067	1.022	1.058	0.955
0.90	1.065	1.027	0.994	1.029	0.922
0.87	1.042	1.011	0.975	1.010	0.881
0.83	1.025	0.987	0.956	0.989	0.831
0.80	0.985	0.931	0.910	0.942	0.808
0.77	0.941	0.909	0.879	0.909	0.799
0.73	0.907	0.882	0.850	0.880	0.772
0.70	0.885	0.826	0.813	0.841	0.690
0.67	0.837	0.803	0.779	0.806	0.700
0.63	0.804	0.757	0.741	0.767	0.652
0.60	0.756	0.729	0.705	0.730	0.596
0.57	0.746	0.702	0.688	0.712	0.587
0.53	0.706	0.699	0.667	0.691	0.540
0.50	0.691	0.628	0.627	0.649	0.508
0.47	0.631	0.598	0.584	0.604	0.505
0.43	0.574	0.556	0.537	0.556	0.479
0.40	0.553	0.536	0.517	0.535	0.410
0.37	0.534	0.498	0.490	0.507	0.386
0.33	0.497	0.459	0.454	0.470	0.339
0.30	0.451	0.394	0.402	0.416	0.335
0.27	0.413	0.392	0.383	0.396	0.287
0.23	0.372	0.361	0.348	0.360	0.236
0.20	0.360	0.334	0.330	0.341	0.241
0.17	0.346	0.285	0.300	0.310	0.194
0.13	0.288	0.229	0.246	0.254	0.150
0.10	0.255	0.220	0.226	0.234	0.132
0.07	0.205	0.192	0.189	0.195	0.103
0.03	0.187	0.160	0.165	0.171	0.039
0.00	0.171	0.108	0.133	0.137	0.033



Appendix A-12. Load Profile 12

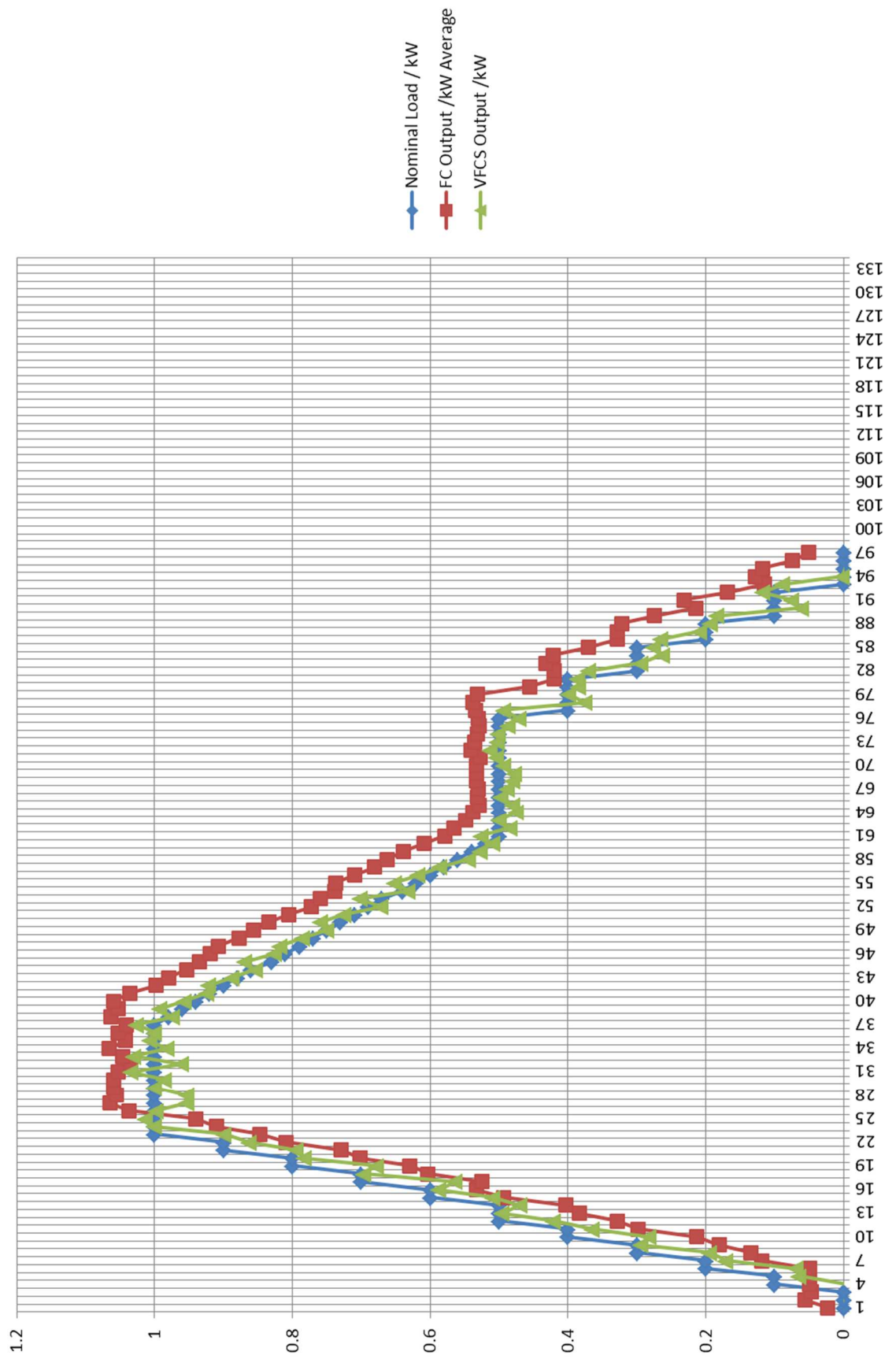
Profile 12 does not increase linearly to 1kW so one can see what happens when the demand fluctuates.



Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.003	0.010	0.056	0.023	-0.005
0.00	0.055	0.057	0.055	0.056	-0.002
0.00	0.048	0.044	0.050	0.048	-0.009
0.10	0.048	0.049	0.050	0.049	-0.002
0.10	0.049	0.049	0.049	0.049	0.065
0.20	0.048	0.051	0.050	0.050	0.069
0.20	0.166	0.049	0.143	0.119	0.171
0.30	0.118	0.163	0.123	0.135	0.195
0.30	0.228	0.123	0.192	0.181	0.294
0.40	0.219	0.215	0.204	0.213	0.283
0.40	0.354	0.203	0.338	0.298	0.366
0.50	0.330	0.322	0.335	0.329	0.421
0.50	0.428	0.325	0.398	0.384	0.496
0.50	0.409	0.419	0.383	0.404	0.470
0.60	0.526	0.428	0.528	0.494	0.509
0.60	0.527	0.543	0.528	0.533	0.587
0.70	0.526	0.520	0.528	0.525	0.564
0.70	0.661	0.523	0.626	0.603	0.696
0.80	0.620	0.647	0.622	0.629	0.679
0.80	0.753	0.623	0.728	0.702	0.783
0.90	0.722	0.745	0.720	0.729	0.794
0.90	0.851	0.739	0.836	0.809	0.863
1.00	0.842	0.851	0.848	0.847	0.899
1.00	0.957	0.823	0.951	0.910	1.001
1.00	0.923	0.949	0.951	0.941	1.014
1.00	1.081	0.931	1.100	1.037	0.998
1.00	1.073	1.098	1.024	1.065	0.954
1.00	1.048	1.073	1.045	1.056	0.954
1.00	1.068	1.036	1.075	1.060	1.001
1.00	1.042	1.070	1.064	1.059	0.986
1.00	1.043	1.076	1.040	1.053	1.035
1.00	1.032	1.019	1.051	1.034	0.961
1.00	1.036	1.047	1.055	1.046	1.031
1.00	1.064	1.082	1.050	1.065	0.982
1.00	1.057	1.044	1.027	1.043	1.007
1.00	1.065	1.047	1.046	1.053	1.000

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
1.00	1.041	1.042	1.038	1.040	1.026
0.98	1.050	1.078	1.063	1.063	0.974
0.96	1.039	1.078	1.043	1.053	0.993
0.94	1.043	1.078	1.058	1.060	0.957
0.92	1.020	1.062	1.025	1.036	0.924
0.90	0.988	1.020	0.984	0.997	0.921
0.88	0.969	0.996	0.975	0.980	0.888
0.86	0.950	0.972	0.938	0.953	0.854
0.83	0.938	0.945	0.921	0.934	0.870
0.81	0.901	0.925	0.932	0.919	0.827
0.79	0.899	0.931	0.891	0.907	0.818
0.77	0.867	0.909	0.855	0.877	0.785
0.75	0.846	0.871	0.850	0.856	0.751
0.73	0.826	0.855	0.823	0.834	0.760
0.71	0.793	0.821	0.800	0.805	0.725
0.69	0.762	0.789	0.767	0.772	0.671
0.67	0.735	0.770	0.773	0.759	0.702
0.64	0.726	0.767	0.723	0.739	0.632
0.62	0.733	0.751	0.727	0.737	0.652
0.60	0.697	0.726	0.706	0.710	0.618
0.58	0.665	0.703	0.674	0.681	0.587
0.56	0.648	0.681	0.657	0.662	0.545
0.54	0.628	0.650	0.639	0.639	0.528
0.52	0.593	0.630	0.605	0.609	0.510
0.50	0.560	0.602	0.577	0.579	0.527
0.50	0.570	0.564	0.563	0.566	0.484
0.50	0.559	0.541	0.547	0.549	0.501
0.50	0.522	0.558	0.535	0.538	0.475
0.50	0.532	0.530	0.525	0.529	0.480
0.50	0.531	0.531	0.532	0.531	0.497
0.50	0.527	0.532	0.531	0.530	0.488
0.50	0.529	0.529	0.542	0.533	0.481
0.50	0.543	0.527	0.531	0.533	0.478
0.50	0.528	0.543	0.529	0.533	0.494
0.50	0.527	0.525	0.530	0.527	0.504
0.50	0.542	0.539	0.543	0.541	0.513
0.50	0.541	0.543	0.522	0.535	0.503
0.50	0.525	0.528	0.542	0.532	0.501
0.50	0.525	0.536	0.525	0.528	0.487
0.50	0.540	0.524	0.527	0.530	0.471
0.40	0.532	0.538	0.533	0.535	0.494
0.40	0.538	0.537	0.539	0.538	0.375
0.40	0.538	0.524	0.533	0.532	0.399
0.40	0.400	0.522	0.443	0.455	0.385
0.40	0.436	0.416	0.410	0.420	0.386
0.30	0.416	0.414	0.432	0.421	0.371
0.30	0.414	0.448	0.433	0.432	0.295
0.30	0.439	0.406	0.418	0.421	0.263
0.30	0.323	0.440	0.350	0.371	0.277
0.20	0.331	0.316	0.340	0.329	0.266
0.20	0.311	0.335	0.339	0.329	0.210
0.20	0.307	0.332	0.327	0.322	0.193
0.10	0.219	0.337	0.268	0.274	0.184
0.10	0.208	0.243	0.193	0.214	0.061
0.10	0.255	0.231	0.210	0.232	0.076
0.10	0.125	0.256	0.123	0.168	0.118

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.118	0.105	0.123	0.115	0.088
0.00	0.127	0.120	0.136	0.128	0.002
0.00	0.118	0.122	0.113	0.118	-0.003
0.00	0.049	0.124	0.052	0.075	-0.011
0.00	0.051	0.050	0.052	0.051	-0.004



Appendix A-13. Load Profile 13

Profile 13 takes varies the demand over 35 minutes. This is the longest simulation run for the fuel cell.



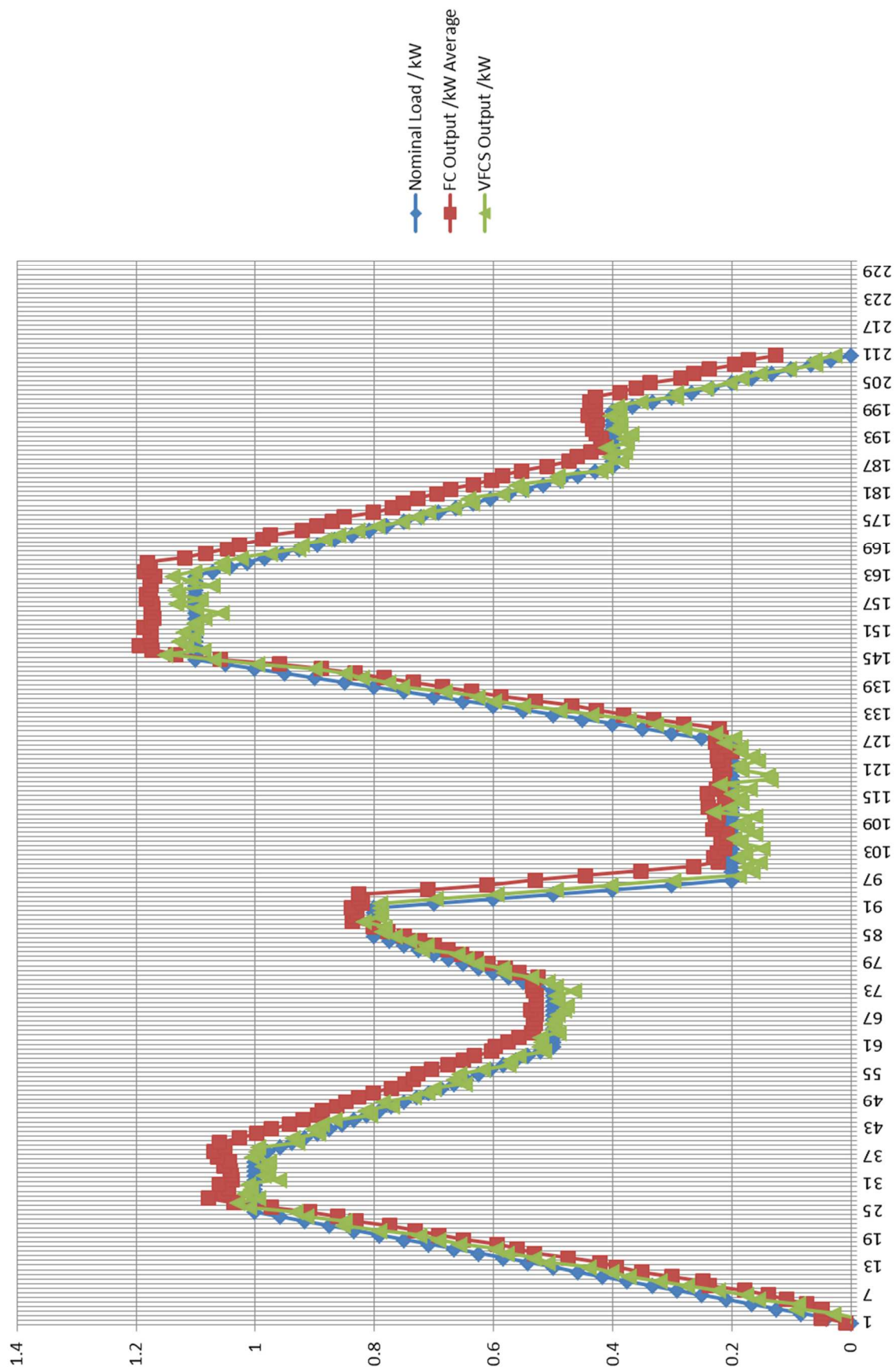
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.009	0.010	0.010	0.009	-0.002
0.04	0.045	0.053	0.053	0.050	-0.005
0.08	0.051	0.047	0.047	0.048	0.029
0.13	0.051	0.049	0.048	0.049	0.091
0.17	0.071	0.074	0.078	0.075	0.089
0.21	0.087	0.119	0.116	0.107	0.156
0.25	0.136	0.142	0.140	0.139	0.176
0.29	0.173	0.182	0.180	0.178	0.223
0.33	0.210	0.252	0.251	0.238	0.274
0.38	0.240	0.245	0.261	0.249	0.321
0.42	0.283	0.307	0.311	0.300	0.373
0.46	0.355	0.347	0.352	0.351	0.402
0.50	0.372	0.404	0.405	0.393	0.440
0.54	0.426	0.418	0.422	0.422	0.509
0.58	0.477	0.478	0.469	0.475	0.531
0.63	0.526	0.537	0.533	0.532	0.577
0.67	0.549	0.560	0.570	0.560	0.595
0.71	0.586	0.600	0.597	0.595	0.656
0.75	0.641	0.652	0.659	0.651	0.692
0.79	0.678	0.709	0.690	0.692	0.725
0.83	0.735	0.724	0.734	0.731	0.792
0.88	0.771	0.772	0.782	0.775	0.852
0.92	0.829	0.836	0.830	0.831	0.850
0.96	0.851	0.873	0.860	0.861	0.913
1.00	0.913	0.909	0.905	0.909	0.932
1.00	0.970	0.973	0.976	0.973	1.010
1.00	1.025	1.027	1.053	1.035	1.030
1.00	1.054	1.098	1.085	1.079	0.995
1.00	1.038	1.075	1.046	1.053	1.017
1.00	1.031	1.062	1.043	1.046	1.007
1.00	1.058	1.054	1.071	1.061	1.011
1.00	1.037	1.048	1.033	1.039	0.960
1.00	1.063	1.029	1.030	1.041	0.986
1.00	1.029	1.059	1.039	1.042	0.978

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
1.00	1.048	1.059	1.051	1.052	0.987
1.00	1.023	1.049	1.059	1.043	0.977
1.00	1.066	1.049	1.075	1.063	1.005
0.98	1.057	1.068	1.081	1.069	0.997
0.96	1.029	1.052	1.071	1.051	0.994
0.94	1.059	1.060	1.062	1.060	0.929
0.92	1.025	1.035	1.021	1.027	0.937
0.90	0.994	0.997	1.001	0.998	0.893
0.88	0.972	0.973	0.975	0.973	0.902
0.85	0.941	0.944	0.943	0.943	0.887
0.83	0.914	0.924	0.922	0.920	0.866
0.81	0.892	0.894	0.902	0.896	0.807
0.79	0.863	0.889	0.909	0.887	0.815
0.77	0.858	0.857	0.872	0.862	0.770
0.75	0.844	0.850	0.852	0.848	0.785
0.73	0.829	0.823	0.825	0.826	0.733
0.71	0.801	0.808	0.795	0.801	0.710
0.69	0.770	0.771	0.774	0.772	0.700
0.67	0.754	0.740	0.752	0.749	0.647
0.65	0.737	0.728	0.738	0.735	0.666
0.63	0.727	0.729	0.727	0.728	0.657
0.60	0.708	0.704	0.701	0.704	0.617
0.58	0.678	0.678	0.676	0.677	0.574
0.56	0.652	0.651	0.651	0.651	0.572
0.54	0.632	0.632	0.632	0.632	0.558
0.52	0.610	0.602	0.597	0.603	0.515
0.50	0.603	0.590	0.600	0.598	0.523
0.50	0.573	0.579	0.577	0.576	0.520
0.50	0.566	0.553	0.555	0.558	0.521
0.50	0.538	0.539	0.532	0.537	0.490
0.50	0.537	0.532	0.532	0.534	0.498
0.50	0.526	0.531	0.536	0.531	0.501
0.50	0.532	0.545	0.522	0.533	0.496
0.50	0.533	0.529	0.524	0.529	0.491
0.50	0.529	0.541	0.542	0.538	0.481
0.50	0.532	0.526	0.526	0.528	0.477
0.50	0.529	0.527	0.529	0.528	0.492
0.50	0.528	0.527	0.532	0.529	0.495
0.50	0.540	0.526	0.534	0.533	0.464
0.53	0.529	0.534	0.539	0.534	0.495
0.55	0.527	0.531	0.539	0.532	0.508
0.58	0.527	0.525	0.523	0.525	0.536
0.60	0.550	0.556	0.568	0.558	0.582
0.63	0.590	0.576	0.574	0.580	0.585
0.65	0.613	0.606	0.611	0.610	0.628
0.68	0.629	0.628	0.632	0.630	0.644
0.70	0.644	0.659	0.657	0.653	0.660
0.73	0.677	0.674	0.680	0.677	0.720
0.75	0.692	0.704	0.702	0.699	0.712
0.78	0.718	0.727	0.727	0.724	0.741
0.80	0.747	0.753	0.751	0.750	0.766
0.80	0.775	0.782	0.777	0.778	0.786
0.80	0.800	0.803	0.803	0.802	0.783
0.80	0.832	0.845	0.834	0.837	0.818
0.80	0.823	0.850	0.829	0.834	0.792
0.80	0.825	0.835	0.829	0.830	0.789

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.80	0.854	0.832	0.830	0.838	0.790
0.70	0.813	0.821	0.825	0.820	0.790
0.60	0.815	0.827	0.836	0.826	0.696
0.50	0.830	0.828	0.822	0.827	0.594
0.40	0.712	0.717	0.700	0.710	0.495
0.30	0.611	0.618	0.603	0.611	0.403
0.20	0.530	0.532	0.529	0.530	0.298
0.20	0.446	0.444	0.447	0.446	0.188
0.20	0.354	0.354	0.350	0.353	0.164
0.20	0.263	0.266	0.261	0.263	0.175
0.20	0.201	0.230	0.236	0.223	0.152
0.20	0.232	0.216	0.243	0.230	0.189
0.20	0.232	0.227	0.212	0.224	0.177
0.20	0.241	0.183	0.210	0.211	0.147
0.20	0.243	0.204	0.209	0.219	0.185
0.20	0.210	0.208	0.208	0.208	0.196
0.20	0.218	0.206	0.198	0.207	0.161
0.20	0.232	0.241	0.222	0.232	0.175
0.20	0.238	0.212	0.232	0.228	0.190
0.20	0.240	0.196	0.239	0.225	0.178
0.20	0.253	0.194	0.222	0.223	0.159
0.20	0.221	0.225	0.242	0.229	0.230
0.20	0.263	0.257	0.198	0.240	0.202
0.20	0.210	0.204	0.200	0.205	0.183
0.20	0.212	0.236	0.190	0.213	0.186
0.20	0.212	0.252	0.258	0.241	0.200
0.20	0.207	0.231	0.239	0.226	0.169
0.20	0.220	0.218	0.206	0.215	0.220
0.20	0.230	0.212	0.209	0.217	0.135
0.20	0.221	0.229	0.209	0.220	0.139
0.20	0.229	0.196	0.214	0.213	0.184
0.20	0.219	0.220	0.202	0.214	0.188
0.20	0.226	0.220	0.223	0.223	0.155
0.20	0.212	0.242	0.218	0.224	0.165
0.20	0.193	0.214	0.191	0.199	0.185
0.20	0.240	0.187	0.210	0.212	0.185
0.20	0.220	0.241	0.222	0.228	0.213
0.25	0.219	0.189	0.248	0.219	0.196
0.30	0.226	0.217	0.233	0.225	0.227
0.35	0.212	0.210	0.243	0.222	0.279
0.40	0.271	0.281	0.290	0.281	0.326
0.45	0.323	0.336	0.337	0.332	0.373
0.50	0.358	0.388	0.397	0.381	0.435
0.55	0.428	0.438	0.417	0.428	0.489
0.60	0.464	0.473	0.468	0.468	0.550
0.65	0.537	0.514	0.538	0.529	0.599
0.70	0.587	0.588	0.590	0.589	0.626
0.75	0.633	0.636	0.641	0.637	0.681
0.80	0.685	0.687	0.683	0.685	0.754
0.85	0.732	0.736	0.735	0.734	0.776
0.90	0.783	0.783	0.785	0.784	0.821
0.95	0.836	0.833	0.828	0.832	0.849
1.00	0.888	0.891	0.888	0.889	0.900
1.05	0.968	0.957	0.951	0.959	0.996
1.10	1.044	1.065	1.067	1.058	1.069
1.10	1.126	1.120	1.154	1.133	1.150

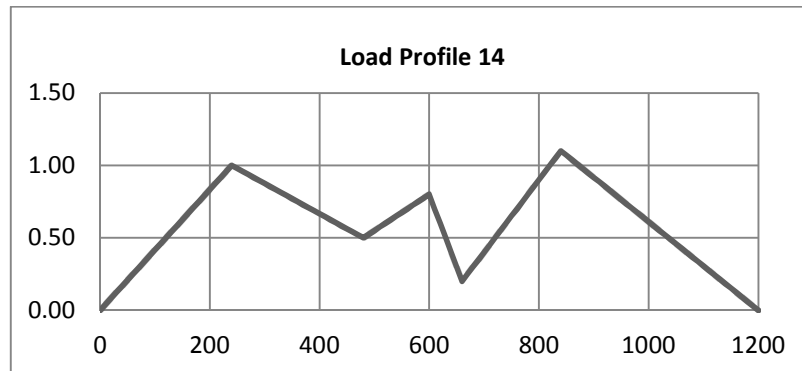
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
1.10	1.142	1.171	1.209	1.174	1.085
1.10	1.193	1.222	1.167	1.194	1.115
1.10	1.166	1.188	1.169	1.174	1.127
1.10	1.171	1.174	1.186	1.177	1.102
1.10	1.171	1.187	1.168	1.175	1.119
1.10	1.168	1.216	1.178	1.187	1.098
1.10	1.160	1.184	1.182	1.175	1.101
1.10	1.177	1.171	1.163	1.170	1.084
1.10	1.169	1.174	1.182	1.175	1.056
1.10	1.171	1.159	1.187	1.172	1.098
1.10	1.164	1.171	1.184	1.173	1.132
1.10	1.184	1.179	1.185	1.183	1.091
1.10	1.171	1.182	1.192	1.182	1.129
1.10	1.173	1.177	1.180	1.177	1.134
1.10	1.176	1.169	1.180	1.175	1.071
1.10	1.166	1.177	1.187	1.177	1.108
1.10	1.178	1.152	1.176	1.169	1.138
1.07	1.179	1.186	1.192	1.186	1.101
1.04	1.167	1.179	1.182	1.176	1.054
1.01	1.174	1.184	1.186	1.181	1.056
0.98	1.102	1.131	1.123	1.119	1.024
0.95	1.069	1.066	1.113	1.082	0.975
0.93	1.052	1.049	1.038	1.046	0.927
0.90	1.027	1.028	1.026	1.027	0.922
0.87	0.996	0.991	0.973	0.987	0.882
0.84	0.982	0.969	0.973	0.975	0.860
0.81	0.920	0.930	0.912	0.920	0.828
0.78	0.895	0.896	0.899	0.897	0.795
0.75	0.864	0.873	0.875	0.871	0.752
0.72	0.853	0.849	0.851	0.851	0.728
0.69	0.797	0.790	0.818	0.802	0.709
0.66	0.771	0.768	0.769	0.770	0.666
0.63	0.746	0.755	0.751	0.751	0.636
0.60	0.727	0.733	0.718	0.726	0.642
0.58	0.704	0.707	0.671	0.694	0.585
0.55	0.662	0.683	0.673	0.672	0.553
0.52	0.618	0.633	0.650	0.634	0.560
0.49	0.598	0.603	0.608	0.603	0.495
0.46	0.588	0.586	0.583	0.585	0.491
0.43	0.558	0.536	0.564	0.553	0.420
0.40	0.505	0.520	0.506	0.510	0.411
0.40	0.475	0.473	0.474	0.474	0.385
0.40	0.461	0.460	0.457	0.460	0.404
0.40	0.429	0.440	0.439	0.436	0.378
0.40	0.416	0.413	0.407	0.412	0.410
0.40	0.412	0.387	0.455	0.418	0.376
0.40	0.389	0.433	0.440	0.420	0.380
0.40	0.445	0.421	0.417	0.428	0.368
0.40	0.435	0.432	0.436	0.434	0.397
0.40	0.427	0.436	0.420	0.428	0.387
0.40	0.451	0.415	0.412	0.426	0.391
0.40	0.435	0.441	0.446	0.441	0.403
0.40	0.429	0.435	0.423	0.429	0.387
0.37	0.433	0.433	0.435	0.434	0.392
0.33	0.431	0.440	0.445	0.439	0.352
0.30	0.431	0.420	0.437	0.429	0.293

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.27	0.381	0.367	0.413	0.387	0.294
0.23	0.367	0.356	0.359	0.361	0.242
0.20	0.339	0.341	0.334	0.338	0.202
0.17	0.285	0.289	0.282	0.285	0.183
0.13	0.275	0.248	0.270	0.264	0.152
0.10	0.235	0.221	0.257	0.238	0.103
0.07	0.196	0.190	0.199	0.195	0.059
0.03	0.172	0.176	0.170	0.173	0.061
0.00	0.128	0.137	0.113	0.126	0.028



Appendix A-14. Load Profile 14

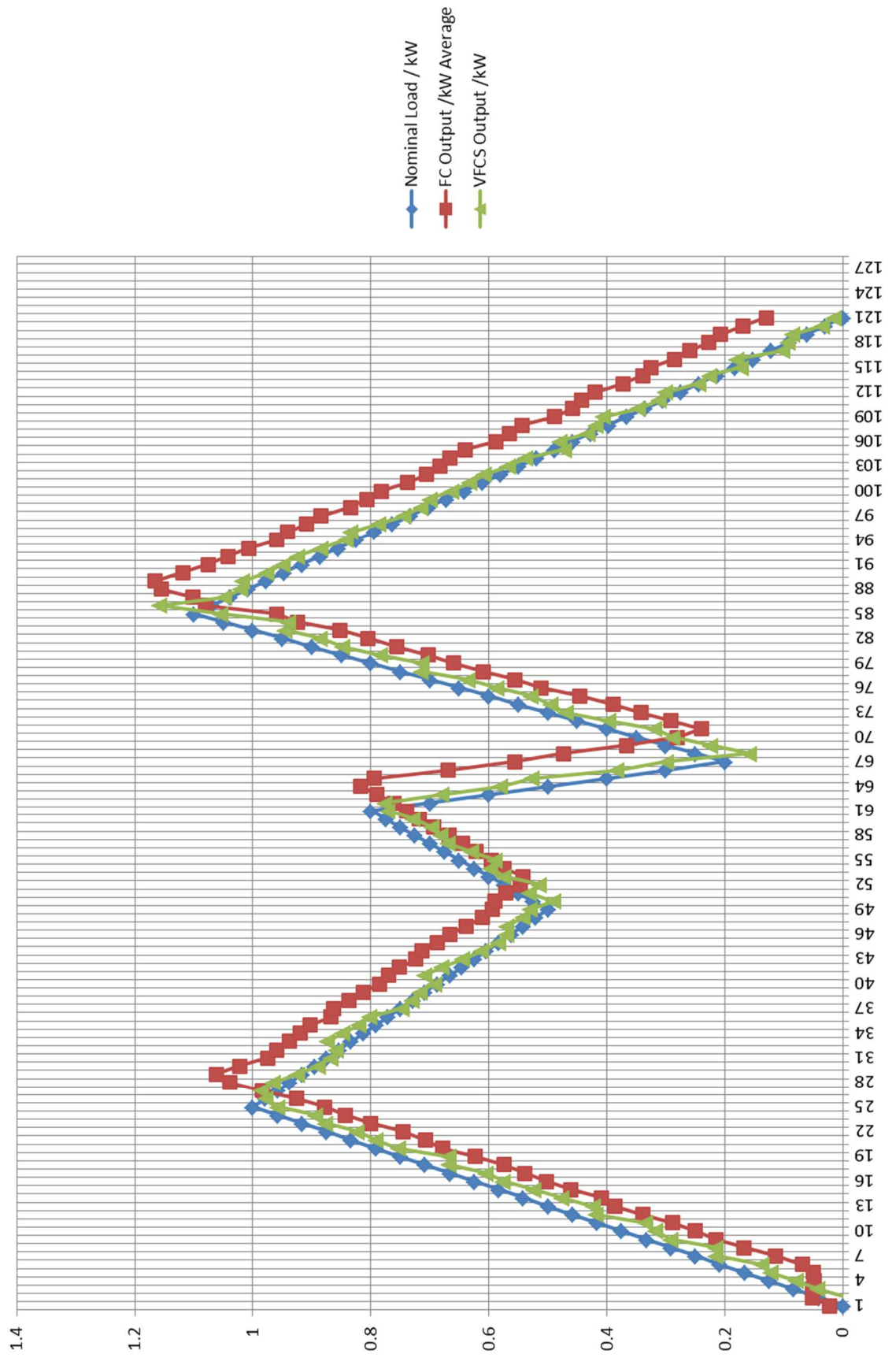
Profile 14 follows a similar demand cycle to Profile 13 however the load is not held for any time at any one value.



Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.010	0.010	0.046	0.022	-0.004
0.04	0.043	0.056	0.056	0.052	-0.008
0.08	0.048	0.055	0.051	0.052	0.042
0.13	0.049	0.049	0.048	0.049	0.079
0.17	0.057	0.047	0.048	0.051	0.122
0.21	0.098	0.057	0.052	0.069	0.137
0.25	0.146	0.110	0.087	0.114	0.216
0.29	0.202	0.145	0.156	0.168	0.215
0.33	0.245	0.192	0.209	0.216	0.292
0.38	0.266	0.231	0.252	0.250	0.317
0.42	0.321	0.268	0.278	0.289	0.335
0.46	0.377	0.318	0.324	0.340	0.418
0.50	0.419	0.363	0.377	0.386	0.423
0.54	0.444	0.405	0.381	0.410	0.477
0.58	0.490	0.450	0.443	0.461	0.524
0.63	0.542	0.477	0.490	0.503	0.576
0.67	0.550	0.536	0.529	0.538	0.604
0.71	0.606	0.554	0.564	0.575	0.667
0.75	0.658	0.600	0.609	0.623	0.668
0.79	0.705	0.662	0.668	0.678	0.753
0.83	0.741	0.683	0.699	0.707	0.791
0.88	0.783	0.728	0.726	0.746	0.823
0.92	0.832	0.784	0.785	0.800	0.876
0.96	0.870	0.831	0.829	0.843	0.893
1.00	0.913	0.862	0.858	0.878	0.958
0.98	0.966	0.910	0.899	0.925	0.978
0.96	1.033	0.970	0.949	0.984	0.986
0.94	1.075	1.026	1.015	1.039	0.965
0.92	1.023	1.094	1.069	1.062	0.924
0.90	0.989	1.057	1.021	1.022	0.888
0.88	0.965	0.980	0.980	0.975	0.867
0.85	0.943	0.967	0.967	0.959	0.858
0.83	0.930	0.944	0.938	0.937	0.873
0.81	0.889	0.951	0.920	0.920	0.848
0.79	0.897	0.898	0.915	0.903	0.820
0.77	0.839	0.864	0.898	0.867	0.802

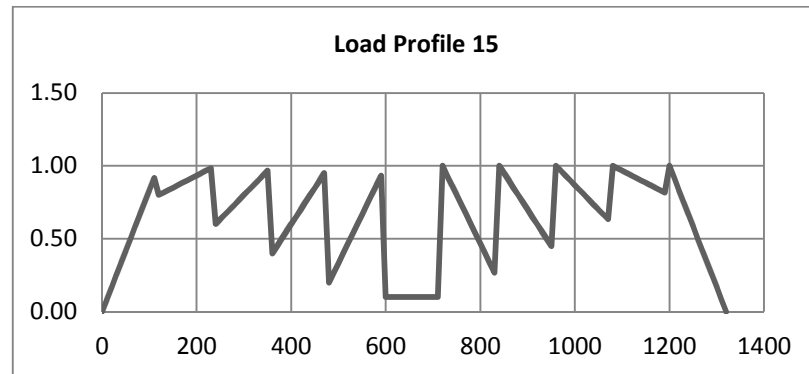
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.75	0.841	0.877	0.873	0.863	0.746
0.73	0.821	0.839	0.851	0.837	0.731
0.71	0.804	0.817	0.815	0.812	0.717
0.69	0.764	0.798	0.795	0.786	0.692
0.67	0.774	0.766	0.768	0.769	0.709
0.65	0.743	0.734	0.775	0.751	0.680
0.63	0.720	0.747	0.704	0.724	0.644
0.60	0.692	0.721	0.725	0.713	0.612
0.58	0.658	0.704	0.698	0.687	0.583
0.56	0.646	0.686	0.666	0.666	0.569
0.54	0.630	0.639	0.645	0.638	0.569
0.52	0.598	0.622	0.611	0.610	0.542
0.50	0.603	0.586	0.592	0.594	0.530
0.53	0.580	0.600	0.590	0.590	0.490
0.55	0.557	0.576	0.582	0.572	0.531
0.58	0.527	0.554	0.558	0.546	0.514
0.60	0.567	0.542	0.520	0.543	0.575
0.63	0.584	0.568	0.573	0.575	0.597
0.65	0.605	0.588	0.591	0.595	0.589
0.68	0.639	0.609	0.618	0.622	0.629
0.70	0.661	0.638	0.636	0.645	0.668
0.73	0.681	0.664	0.660	0.668	0.681
0.75	0.712	0.684	0.683	0.693	0.696
0.78	0.731	0.716	0.709	0.719	0.728
0.80	0.755	0.732	0.733	0.740	0.771
0.70	0.782	0.760	0.742	0.761	0.776
0.60	0.805	0.785	0.779	0.790	0.680
0.50	0.839	0.806	0.805	0.817	0.580
0.40	0.711	0.837	0.834	0.794	0.527
0.30	0.602	0.697	0.709	0.669	0.383
0.20	0.503	0.587	0.576	0.555	0.299
0.25	0.411	0.508	0.501	0.473	0.159
0.30	0.322	0.411	0.368	0.367	0.224
0.35	0.231	0.311	0.299	0.280	0.288
0.40	0.270	0.237	0.214	0.240	0.319
0.45	0.352	0.255	0.265	0.291	0.397
0.50	0.407	0.305	0.315	0.342	0.469
0.55	0.408	0.359	0.399	0.389	0.495
0.60	0.495	0.438	0.406	0.446	0.528
0.65	0.543	0.499	0.493	0.512	0.587
0.70	0.598	0.536	0.533	0.555	0.636
0.75	0.641	0.592	0.596	0.610	0.714
0.80	0.687	0.645	0.650	0.660	0.713
0.85	0.734	0.690	0.685	0.703	0.784
0.90	0.789	0.739	0.739	0.756	0.847
0.95	0.847	0.781	0.785	0.804	0.885
1.00	0.892	0.833	0.831	0.852	0.946
1.05	0.940	0.878	0.956	0.925	0.940
1.10	1.028	0.937	0.913	0.960	1.054
1.07	1.125	1.126	0.991	1.081	1.157
1.04	1.262	0.979	1.062	1.101	1.048
1.01	1.207	1.127	1.131	1.155	1.020
0.98	1.107	1.195	1.194	1.166	1.017
0.95	1.090	1.131	1.135	1.118	0.976
0.92	1.044	1.079	1.104	1.076	0.949
0.89	1.016	1.054	1.055	1.042	0.924

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.86	0.994	1.010	1.017	1.007	0.885
0.83	0.939	0.964	0.972	0.959	0.842
0.79	0.921	0.941	0.960	0.941	0.834
0.76	0.892	0.921	0.914	0.909	0.787
0.73	0.875	0.891	0.885	0.884	0.744
0.70	0.801	0.830	0.872	0.834	0.714
0.67	0.793	0.816	0.811	0.807	0.700
0.64	0.770	0.789	0.788	0.782	0.663
0.61	0.714	0.769	0.731	0.738	0.632
0.58	0.683	0.717	0.714	0.705	0.608
0.55	0.670	0.695	0.681	0.682	0.567
0.52	0.649	0.678	0.669	0.665	0.538
0.49	0.623	0.655	0.641	0.639	0.471
0.46	0.566	0.606	0.591	0.588	0.480
0.43	0.556	0.573	0.567	0.566	0.431
0.40	0.524	0.553	0.554	0.544	0.419
0.37	0.463	0.491	0.510	0.488	0.406
0.34	0.444	0.464	0.467	0.458	0.346
0.31	0.432	0.451	0.444	0.442	0.312
0.28	0.404	0.436	0.418	0.419	0.301
0.24	0.353	0.383	0.380	0.372	0.245
0.21	0.336	0.345	0.338	0.340	0.226
0.18	0.304	0.339	0.332	0.325	0.173
0.15	0.245	0.297	0.315	0.286	0.180
0.12	0.231	0.279	0.269	0.260	0.102
0.09	0.214	0.244	0.225	0.228	0.093
0.06	0.197	0.217	0.206	0.207	0.086
0.03	0.140	0.169	0.197	0.169	0.035
0.00	0.110	0.139	0.141	0.130	0.015



Appendix A-15. Load Profile 15

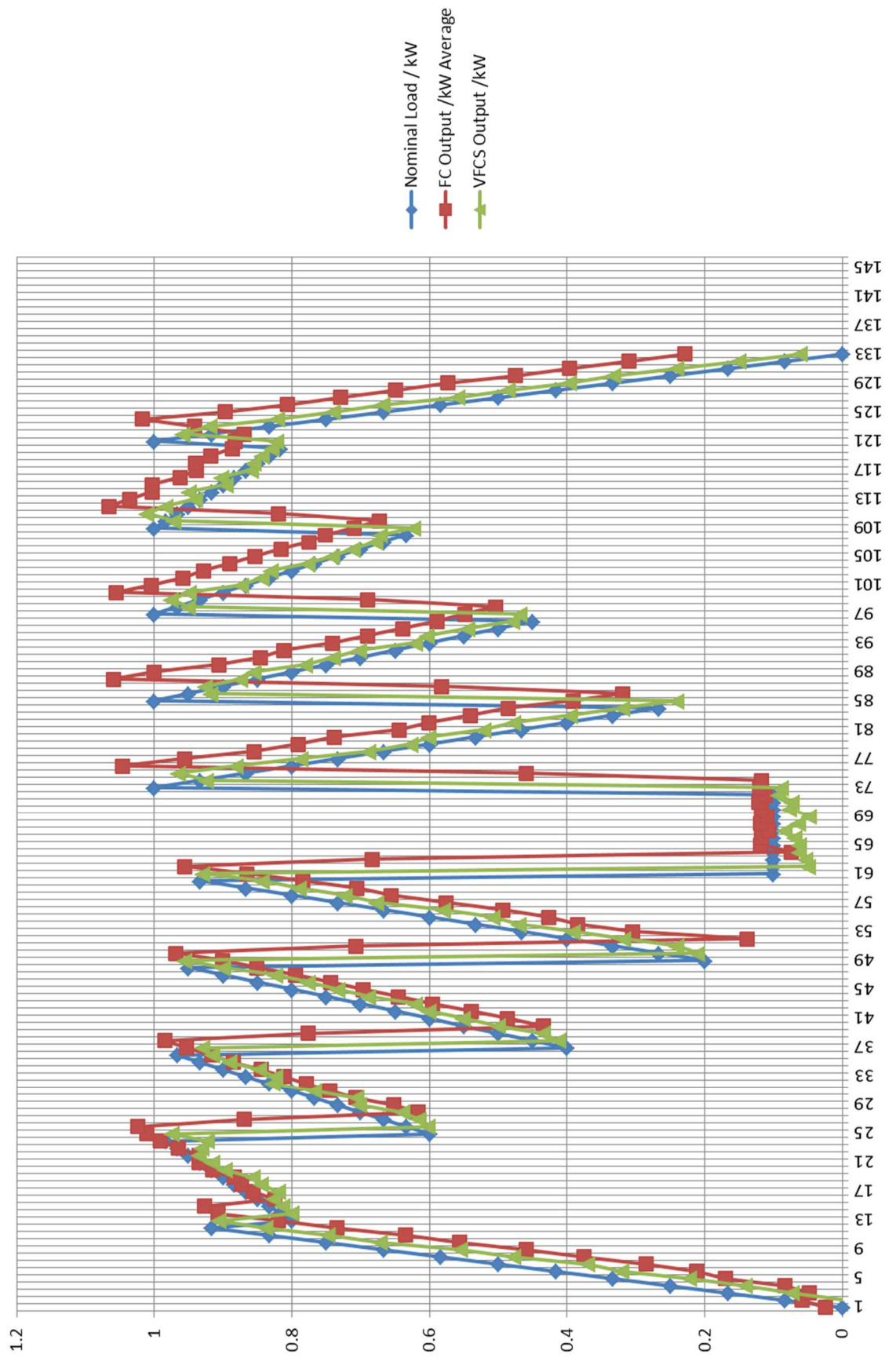
Profile 15 looks at abruptly changing the load demand on the fuel cell do the speed of response can be viewed.



Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.010	0.053	0.010	0.024	-0.008
0.08	0.063	0.049	0.063	0.058	-0.008
0.17	0.047	0.048	0.047	0.048	0.073
0.25	0.049	0.152	0.049	0.083	0.141
0.33	0.166	0.178	0.166	0.170	0.222
0.42	0.186	0.262	0.186	0.211	0.320
0.50	0.251	0.356	0.251	0.286	0.371
0.58	0.350	0.427	0.350	0.376	0.478
0.67	0.421	0.538	0.421	0.460	0.555
0.75	0.529	0.613	0.528	0.556	0.672
0.83	0.605	0.695	0.604	0.635	0.747
0.92	0.706	0.793	0.705	0.735	0.838
0.80	0.791	0.878	0.790	0.819	0.906
0.82	0.869	0.987	0.868	0.908	0.800
0.83	0.983	0.816	0.982	0.927	0.813
0.85	0.810	0.858	0.809	0.825	0.826
0.87	0.850	0.869	0.849	0.856	0.819
0.88	0.872	0.876	0.871	0.873	0.845
0.90	0.873	0.906	0.873	0.884	0.856
0.92	0.911	0.927	0.910	0.916	0.896
0.93	0.938	0.928	0.937	0.934	0.916
0.95	0.921	0.964	0.920	0.935	0.935
0.97	0.956	0.984	0.955	0.965	0.931
0.98	0.985	1.006	0.984	0.992	0.923
0.60	1.010	1.012	1.009	1.010	0.974
0.63	1.011	1.052	1.010	1.024	0.602
0.67	1.035	0.541	1.034	0.870	0.615
0.70	0.600	0.651	0.600	0.617	0.639
0.73	0.642	0.671	0.642	0.652	0.701
0.77	0.702	0.719	0.701	0.707	0.706
0.80	0.739	0.757	0.738	0.744	0.767
0.83	0.764	0.808	0.763	0.779	0.827
0.87	0.804	0.827	0.803	0.811	0.824
0.90	0.828	0.880	0.827	0.845	0.847
0.93	0.873	0.910	0.872	0.885	0.890
0.97	0.909	0.932	0.908	0.916	0.915

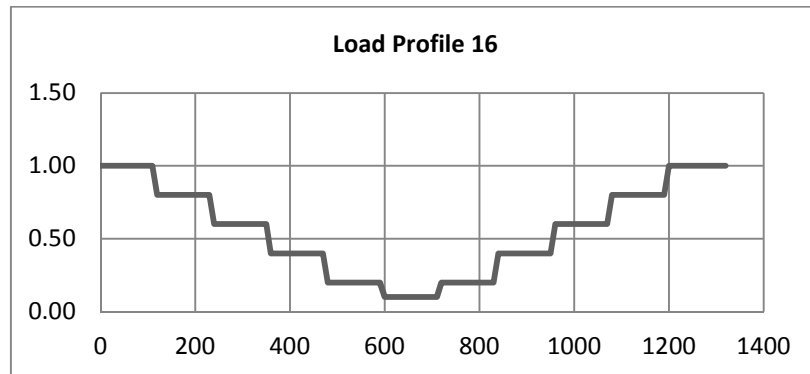
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.40	0.934	0.992	0.933	0.953	0.930
0.45	0.964	1.026	0.963	0.984	0.412
0.50	1.016	0.298	1.015	0.776	0.435
0.55	0.405	0.492	0.405	0.434	0.500
0.60	0.471	0.518	0.471	0.487	0.551
0.65	0.520	0.580	0.520	0.540	0.602
0.70	0.583	0.624	0.582	0.596	0.620
0.75	0.624	0.687	0.624	0.645	0.688
0.80	0.679	0.732	0.679	0.697	0.734
0.85	0.725	0.782	0.725	0.744	0.776
0.90	0.776	0.833	0.775	0.795	0.824
0.95	0.833	0.887	0.832	0.851	0.900
0.20	0.877	0.949	0.877	0.901	0.957
0.27	0.945	1.019	0.944	0.969	0.211
0.33	1.036	0.049	1.035	0.707	0.240
0.40	0.065	0.287	0.065	0.139	0.318
0.47	0.274	0.366	0.274	0.305	0.391
0.53	0.361	0.434	0.361	0.385	0.470
0.60	0.403	0.476	0.403	0.427	0.508
0.67	0.461	0.559	0.461	0.494	0.580
0.73	0.546	0.636	0.545	0.576	0.677
0.80	0.631	0.705	0.630	0.655	0.722
0.87	0.680	0.758	0.679	0.705	0.790
0.93	0.758	0.839	0.757	0.785	0.843
0.10	0.842	0.913	0.841	0.865	0.930
0.10	0.927	1.014	0.926	0.956	0.050
0.10	1.002	0.049	1.001	0.684	0.053
0.10	0.050	0.122	0.049	0.074	0.063
0.10	0.123	0.112	0.123	0.119	0.063
0.10	0.118	0.116	0.118	0.117	0.069
0.10	0.100	0.121	0.100	0.107	0.083
0.10	0.118	0.121	0.118	0.119	0.063
0.10	0.106	0.119	0.105	0.110	0.048
0.10	0.116	0.121	0.116	0.118	0.077
0.10	0.122	0.121	0.122	0.122	0.073
0.10	0.102	0.132	0.102	0.112	0.092
1.00	0.120	0.119	0.120	0.120	0.089
0.93	0.117	0.120	0.116	0.118	0.925
0.87	0.124	1.131	0.124	0.460	0.965
0.80	1.072	0.997	1.071	1.046	0.882
0.73	0.996	0.877	0.995	0.956	0.787
0.67	0.876	0.815	0.875	0.855	0.688
0.60	0.810	0.755	0.809	0.791	0.627
0.53	0.764	0.688	0.763	0.738	0.600
0.47	0.661	0.610	0.661	0.644	0.521
0.40	0.627	0.548	0.626	0.600	0.477
0.33	0.562	0.498	0.561	0.540	0.395
0.27	0.511	0.438	0.510	0.486	0.319
1.00	0.415	0.345	0.415	0.392	0.241
0.95	0.335	0.287	0.335	0.319	0.917
0.90	0.295	1.158	0.294	0.582	0.926
0.85	1.074	1.030	1.073	1.059	0.874
0.80	1.029	0.946	1.028	1.001	0.854
0.75	0.924	0.872	0.923	0.906	0.780
0.70	0.865	0.807	0.864	0.846	0.740
0.65	0.835	0.768	0.834	0.812	0.702

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.60	0.757	0.709	0.757	0.741	0.621
0.55	0.705	0.661	0.704	0.690	0.603
0.50	0.652	0.614	0.652	0.639	0.544
0.45	0.602	0.566	0.601	0.590	0.479
1.00	0.561	0.527	0.560	0.549	0.469
0.97	0.513	0.486	0.513	0.504	0.951
0.93	0.467	1.136	0.466	0.690	0.975
0.90	1.076	1.014	1.075	1.055	0.949
0.87	1.024	0.964	1.023	1.004	0.873
0.83	0.968	0.938	0.967	0.958	0.844
0.80	0.944	0.899	0.943	0.929	0.831
0.77	0.901	0.869	0.900	0.890	0.777
0.73	0.866	0.830	0.865	0.854	0.741
0.70	0.827	0.794	0.827	0.816	0.711
0.67	0.788	0.748	0.787	0.775	0.678
0.63	0.773	0.708	0.773	0.751	0.672
1.00	0.717	0.697	0.716	0.710	0.623
0.98	0.685	0.649	0.684	0.673	0.972
0.97	0.673	1.116	0.672	0.820	1.010
0.95	1.065	1.070	1.064	1.066	0.984
0.93	1.043	1.023	1.042	1.036	0.940
0.92	0.997	1.017	0.996	1.003	0.950
0.90	1.015	0.982	1.014	1.003	0.896
0.88	0.972	0.946	0.971	0.963	0.902
0.87	0.947	0.922	0.946	0.939	0.859
0.85	0.943	0.936	0.942	0.940	0.855
0.83	0.928	0.899	0.927	0.918	0.844
0.82	0.897	0.868	0.896	0.887	0.829
1.00	0.889	0.870	0.888	0.883	0.823
0.92	0.879	0.853	0.878	0.870	0.959
0.83	0.848	1.129	0.847	0.941	0.919
0.75	1.068	0.918	1.067	1.017	0.821
0.67	0.924	0.846	0.923	0.898	0.739
0.58	0.837	0.744	0.837	0.806	0.667
0.50	0.752	0.686	0.751	0.730	0.559
0.42	0.667	0.616	0.666	0.650	0.486
0.33	0.601	0.521	0.600	0.574	0.397
0.25	0.498	0.428	0.498	0.475	0.333
0.17	0.435	0.320	0.435	0.397	0.241
0.08	0.318	0.296	0.318	0.311	0.150
0.00	0.263	0.160	0.262	0.228	0.061



Appendix A-16. Load Profile 16

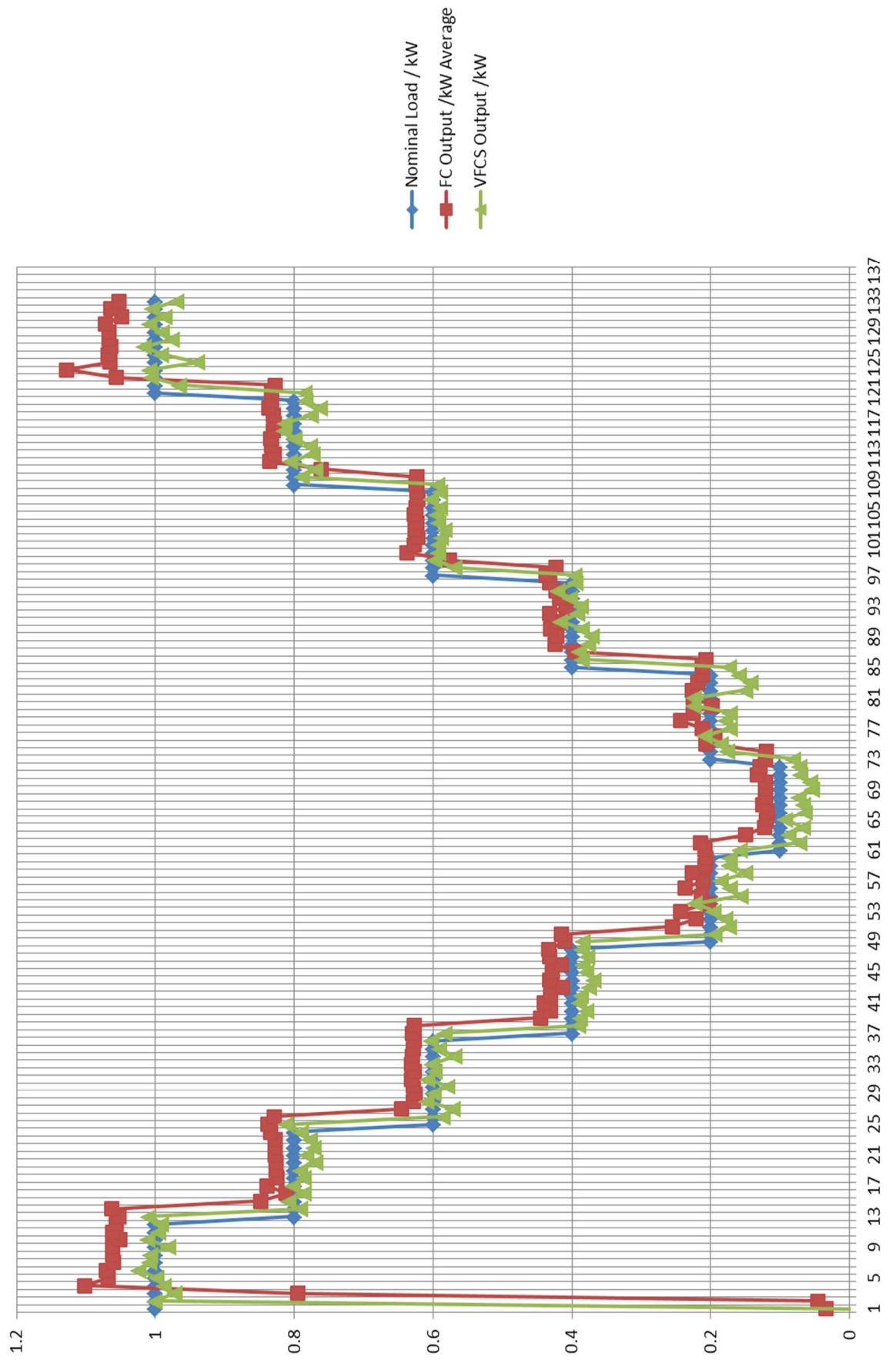
Profile 16 shows even step changes in the load, starting and ending at a high load value.



Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
1.00	0.010	0.042	0.051	0.034	-0.002
1.00	0.041	0.047	0.048	0.045	1.001
1.00	0.047	1.163	1.174	0.795	0.972
1.00	1.167	1.097	1.043	1.102	0.987
1.00	1.093	1.032	1.078	1.068	0.998
1.00	1.079	1.072	1.063	1.071	1.024
1.00	1.064	1.052	1.066	1.060	1.008
1.00	1.061	1.067	1.059	1.062	1.007
1.00	1.068	1.054	1.064	1.062	0.981
1.00	1.061	1.042	1.049	1.051	1.011
1.00	1.086	1.060	1.040	1.062	0.996
1.00	1.047	1.066	1.056	1.056	0.991
0.80	1.051	1.058	1.049	1.053	1.009
0.80	1.080	1.055	1.054	1.063	0.792
0.80	1.061	0.734	0.751	0.849	0.807
0.80	0.777	0.828	0.829	0.811	0.786
0.80	0.858	0.831	0.830	0.839	0.802
0.80	0.822	0.827	0.826	0.825	0.786
0.80	0.824	0.825	0.829	0.826	0.791
0.80	0.832	0.818	0.827	0.826	0.769
0.80	0.821	0.827	0.835	0.828	0.781
0.80	0.826	0.830	0.826	0.827	0.771
0.80	0.824	0.835	0.822	0.827	0.777
0.80	0.854	0.829	0.821	0.835	0.790
0.60	0.829	0.829	0.856	0.838	0.812
0.60	0.835	0.829	0.822	0.829	0.585
0.60	0.832	0.552	0.552	0.645	0.571
0.60	0.627	0.628	0.630	0.628	0.609
0.60	0.620	0.631	0.627	0.626	0.599
0.60	0.630	0.630	0.626	0.629	0.579
0.60	0.631	0.628	0.632	0.630	0.607
0.60	0.628	0.633	0.621	0.627	0.598
0.60	0.632	0.632	0.628	0.631	0.601
0.60	0.633	0.630	0.625	0.629	0.569
0.60	0.633	0.629	0.624	0.629	0.591
0.60	0.629	0.627	0.625	0.627	0.603

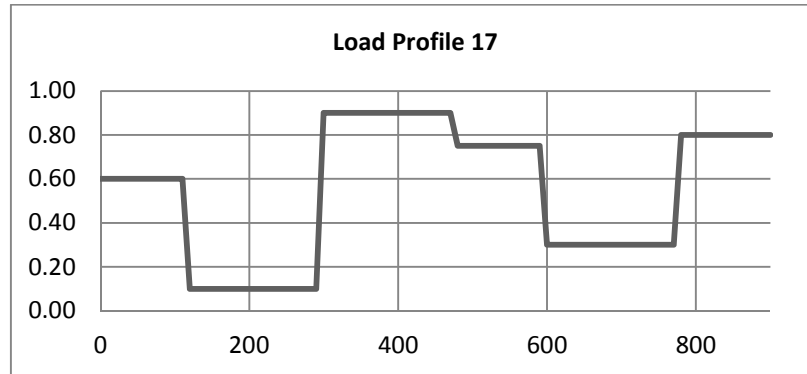
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.40	0.630	0.633	0.628	0.630	0.583
0.40	0.628	0.626	0.626	0.627	0.390
0.40	0.634	0.349	0.352	0.445	0.387
0.40	0.421	0.428	0.443	0.431	0.379
0.40	0.426	0.451	0.443	0.440	0.389
0.40	0.428	0.436	0.428	0.431	0.386
0.40	0.433	0.405	0.401	0.413	0.375
0.40	0.434	0.438	0.423	0.432	0.369
0.40	0.432	0.429	0.424	0.428	0.378
0.40	0.396	0.419	0.431	0.415	0.383
0.40	0.430	0.420	0.446	0.432	0.377
0.40	0.435	0.434	0.430	0.433	0.385
0.20	0.440	0.398	0.390	0.409	0.384
0.20	0.416	0.411	0.419	0.416	0.194
0.20	0.436	0.167	0.161	0.255	0.173
0.20	0.238	0.206	0.221	0.221	0.179
0.20	0.257	0.218	0.255	0.243	0.195
0.20	0.197	0.215	0.198	0.203	0.222
0.20	0.209	0.236	0.197	0.214	0.157
0.20	0.231	0.233	0.247	0.237	0.172
0.20	0.224	0.216	0.191	0.211	0.184
0.20	0.258	0.204	0.218	0.227	0.150
0.20	0.215	0.213	0.197	0.208	0.173
0.20	0.218	0.196	0.206	0.207	0.172
0.10	0.202	0.215	0.206	0.208	0.157
0.10	0.207	0.240	0.197	0.214	0.071
0.10	0.213	0.112	0.122	0.149	0.088
0.10	0.121	0.123	0.124	0.123	0.067
0.10	0.115	0.123	0.121	0.120	0.092
0.10	0.127	0.101	0.125	0.118	0.064
0.10	0.124	0.123	0.127	0.125	0.066
0.10	0.127	0.119	0.119	0.122	0.073
0.10	0.120	0.123	0.122	0.122	0.053
0.10	0.118	0.122	0.124	0.121	0.056
0.10	0.156	0.120	0.122	0.133	0.071
0.10	0.118	0.123	0.144	0.128	0.072
0.20	0.121	0.122	0.122	0.122	0.080
0.20	0.120	0.123	0.117	0.120	0.176
0.20	0.124	0.249	0.249	0.207	0.185
0.20	0.202	0.185	0.196	0.194	0.208
0.20	0.190	0.218	0.230	0.212	0.172
0.20	0.253	0.253	0.225	0.244	0.178
0.20	0.207	0.257	0.211	0.225	0.172
0.20	0.189	0.204	0.200	0.198	0.224
0.20	0.204	0.240	0.231	0.225	0.224
0.20	0.246	0.213	0.221	0.227	0.150
0.20	0.235	0.225	0.196	0.218	0.142
0.20	0.236	0.218	0.183	0.213	0.159
0.40	0.217	0.207	0.214	0.212	0.173
0.40	0.216	0.204	0.203	0.207	0.385
0.40	0.240	0.468	0.479	0.395	0.389
0.40	0.428	0.424	0.419	0.424	0.376
0.40	0.435	0.425	0.403	0.421	0.371
0.40	0.416	0.444	0.432	0.430	0.384
0.40	0.414	0.428	0.420	0.421	0.416
0.40	0.433	0.437	0.426	0.432	0.392

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.40	0.414	0.411	0.401	0.409	0.386
0.40	0.415	0.412	0.427	0.418	0.403
0.40	0.420	0.417	0.432	0.423	0.420
0.40	0.445	0.435	0.414	0.432	0.394
0.60	0.450	0.425	0.434	0.437	0.396
0.60	0.431	0.428	0.411	0.423	0.568
0.60	0.408	0.660	0.661	0.576	0.597
0.60	0.657	0.629	0.625	0.637	0.592
0.60	0.624	0.628	0.627	0.627	0.592
0.60	0.627	0.623	0.615	0.622	0.588
0.60	0.624	0.625	0.629	0.626	0.583
0.60	0.615	0.624	0.630	0.623	0.592
0.60	0.626	0.624	0.632	0.628	0.594
0.60	0.621	0.629	0.624	0.624	0.590
0.60	0.622	0.620	0.625	0.622	0.602
0.60	0.622	0.622	0.625	0.623	0.589
0.80	0.621	0.626	0.627	0.625	0.594
0.80	0.622	0.623	0.623	0.623	0.789
0.80	0.626	0.823	0.833	0.761	0.769
0.80	0.847	0.834	0.823	0.835	0.805
0.80	0.829	0.830	0.829	0.829	0.773
0.80	0.833	0.824	0.842	0.833	0.777
0.80	0.839	0.832	0.830	0.834	0.799
0.80	0.833	0.832	0.827	0.830	0.815
0.80	0.838	0.825	0.823	0.829	0.813
0.80	0.840	0.837	0.813	0.830	0.776
0.80	0.830	0.825	0.852	0.836	0.762
0.80	0.848	0.828	0.822	0.832	0.783
1.00	0.832	0.845	0.820	0.832	0.784
1.00	0.828	0.830	0.825	0.828	0.966
1.00	0.817	1.291	1.061	1.056	1.005
1.00	1.133	1.125	1.126	1.128	1.008
1.00	1.117	1.054	1.025	1.065	0.939
1.00	1.083	1.039	1.084	1.069	0.991
1.00	1.080	1.039	1.073	1.064	1.015
1.00	1.043	1.067	1.092	1.067	0.975
1.00	1.091	1.064	1.046	1.067	0.991
1.00	1.084	1.051	1.080	1.072	1.008
1.00	1.062	1.034	1.050	1.049	0.986
1.00	1.067	1.062	1.065	1.064	1.005
1.00	1.053	1.077	1.026	1.052	0.970



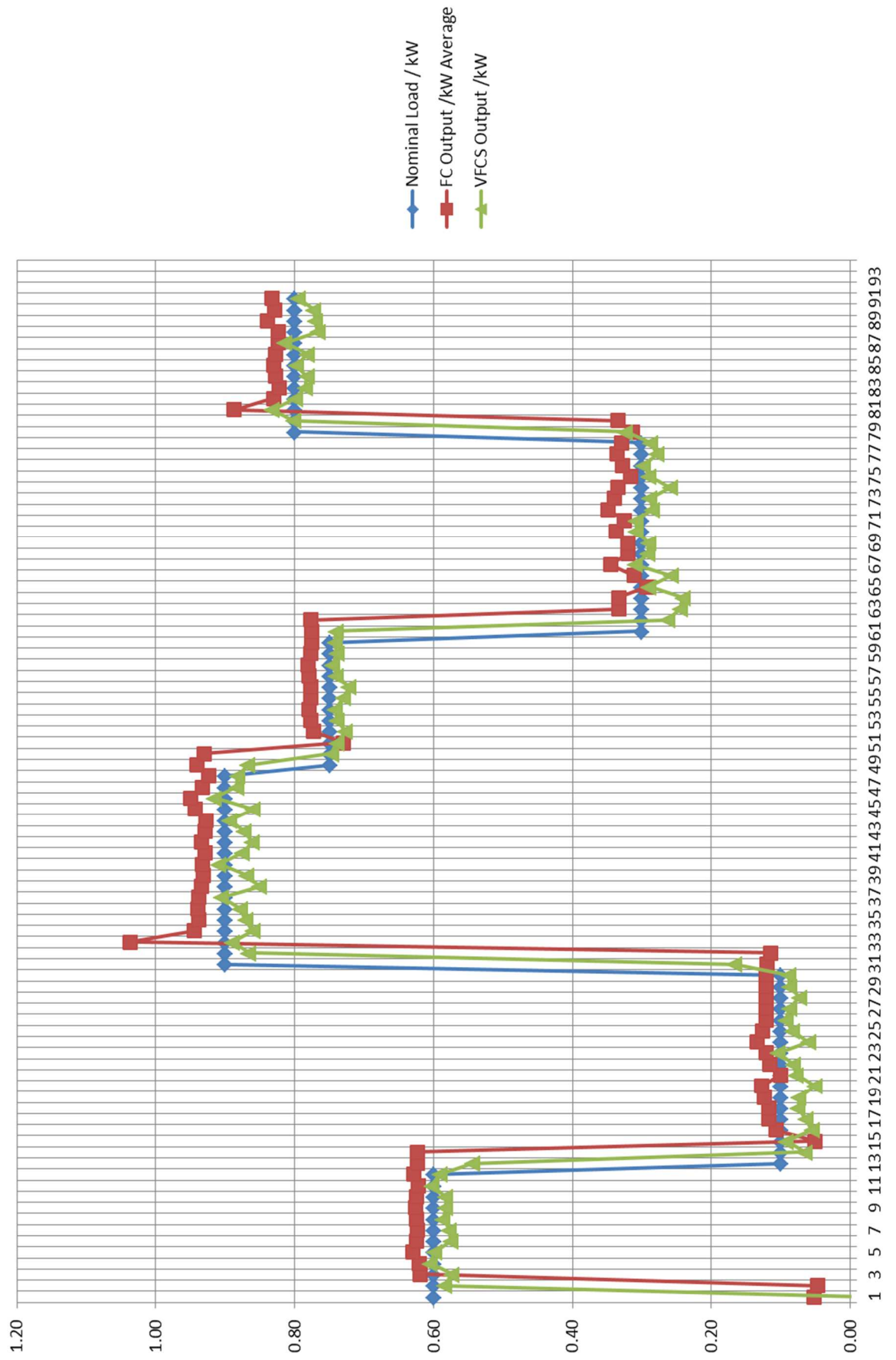
Appendix A-17. Load Profile 17

Profile 17 shows large changes in demand. The changes are abrupt but the fuel cell is held at these load values.



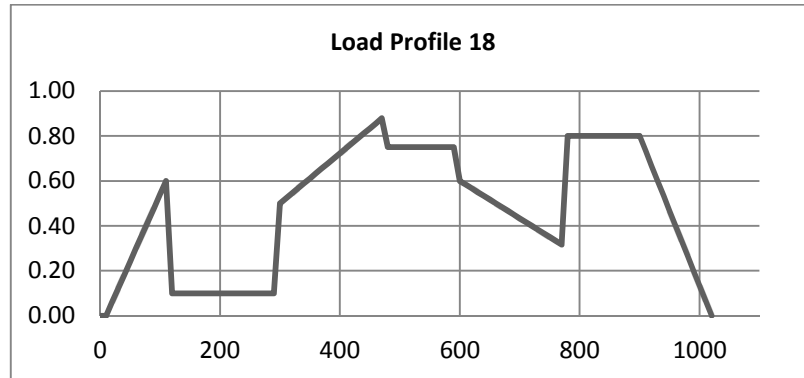
Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.60	0.052	0.052	0.052	0.052	-0.011
0.60	0.047	0.048	0.047	0.047	0.584
0.60	0.617	0.624	0.617	0.619	0.574
0.60	0.619	0.625	0.618	0.620	0.605
0.60	0.628	0.634	0.627	0.629	0.599
0.60	0.623	0.629	0.622	0.625	0.575
0.60	0.621	0.628	0.621	0.623	0.577
0.60	0.622	0.629	0.622	0.624	0.587
0.60	0.624	0.630	0.623	0.626	0.582
0.60	0.623	0.629	0.622	0.625	0.583
0.60	0.620	0.626	0.620	0.622	0.603
0.60	0.627	0.633	0.626	0.629	0.591
0.10	0.622	0.628	0.621	0.624	0.544
0.10	0.622	0.628	0.621	0.624	0.065
0.10	0.050	0.051	0.050	0.050	0.092
0.10	0.107	0.108	0.107	0.107	0.055
0.10	0.117	0.118	0.116	0.117	0.064
0.10	0.116	0.118	0.116	0.117	0.075
0.10	0.123	0.125	0.123	0.124	0.074
0.10	0.127	0.128	0.126	0.127	0.050
0.10	0.101	0.102	0.100	0.101	0.078
0.10	0.116	0.117	0.116	0.116	0.082
0.10	0.121	0.122	0.121	0.121	0.104
0.10	0.134	0.135	0.134	0.134	0.060
0.10	0.126	0.127	0.125	0.126	0.083
0.10	0.121	0.122	0.121	0.122	0.093
0.10	0.121	0.122	0.121	0.122	0.088
0.10	0.121	0.122	0.120	0.121	0.073
0.10	0.120	0.121	0.120	0.120	0.087
0.10	0.121	0.122	0.121	0.121	0.088
0.90	0.119	0.121	0.119	0.120	0.166
0.90	0.114	0.115	0.114	0.114	0.866
0.90	1.033	1.044	1.032	1.036	0.890
0.90	0.942	0.952	0.941	0.945	0.860
0.90	0.936	0.945	0.935	0.939	0.871
0.90	0.936	0.946	0.935	0.939	0.878

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.90	0.936	0.945	0.935	0.938	0.905
0.90	0.932	0.941	0.931	0.934	0.851
0.90	0.929	0.938	0.928	0.932	0.870
0.90	0.930	0.940	0.929	0.933	0.909
0.90	0.926	0.935	0.925	0.928	0.876
0.90	0.931	0.940	0.930	0.934	0.861
0.90	0.926	0.935	0.925	0.929	0.873
0.90	0.925	0.935	0.924	0.928	0.893
0.90	0.941	0.950	0.940	0.944	0.860
0.90	0.947	0.956	0.946	0.950	0.916
0.90	0.930	0.939	0.929	0.932	0.884
0.90	0.921	0.930	0.920	0.923	0.882
0.75	0.938	0.947	0.937	0.940	0.867
0.75	0.927	0.936	0.926	0.930	0.747
0.75	0.728	0.735	0.727	0.730	0.739
0.75	0.770	0.778	0.769	0.773	0.727
0.75	0.774	0.782	0.774	0.777	0.740
0.75	0.777	0.785	0.776	0.779	0.741
0.75	0.774	0.782	0.773	0.776	0.731
0.75	0.774	0.782	0.773	0.776	0.722
0.75	0.776	0.784	0.776	0.779	0.740
0.75	0.779	0.786	0.778	0.781	0.745
0.75	0.775	0.783	0.774	0.777	0.740
0.75	0.773	0.781	0.772	0.775	0.742
0.30	0.773	0.781	0.772	0.775	0.741
0.30	0.774	0.782	0.773	0.776	0.263
0.30	0.332	0.336	0.332	0.333	0.245
0.30	0.333	0.336	0.332	0.334	0.241
0.30	0.292	0.295	0.291	0.293	0.290
0.30	0.311	0.314	0.310	0.311	0.258
0.30	0.344	0.348	0.344	0.345	0.310
0.30	0.319	0.322	0.318	0.320	0.291
0.30	0.319	0.322	0.319	0.320	0.291
0.30	0.335	0.339	0.335	0.336	0.308
0.30	0.324	0.328	0.324	0.325	0.308
0.30	0.348	0.352	0.348	0.349	0.285
0.30	0.339	0.342	0.339	0.340	0.289
0.30	0.333	0.336	0.332	0.334	0.259
0.30	0.315	0.319	0.315	0.316	0.290
0.30	0.327	0.330	0.326	0.328	0.297
0.30	0.334	0.338	0.334	0.335	0.278
0.30	0.328	0.331	0.328	0.329	0.288
0.80	0.312	0.315	0.312	0.313	0.323
0.80	0.334	0.337	0.333	0.335	0.802
0.80	0.884	0.893	0.884	0.887	0.832
0.80	0.828	0.836	0.827	0.831	0.798
0.80	0.820	0.828	0.819	0.823	0.785
0.80	0.825	0.833	0.824	0.827	0.782
0.80	0.828	0.836	0.827	0.830	0.798
0.80	0.825	0.833	0.824	0.827	0.782
0.80	0.822	0.830	0.821	0.824	0.814
0.80	0.821	0.830	0.821	0.824	0.767
0.80	0.837	0.845	0.836	0.840	0.770
0.80	0.827	0.835	0.826	0.829	0.772
0.80	0.824	0.832	0.841	0.832	0.795



Appendix A-18. Load Profile 18

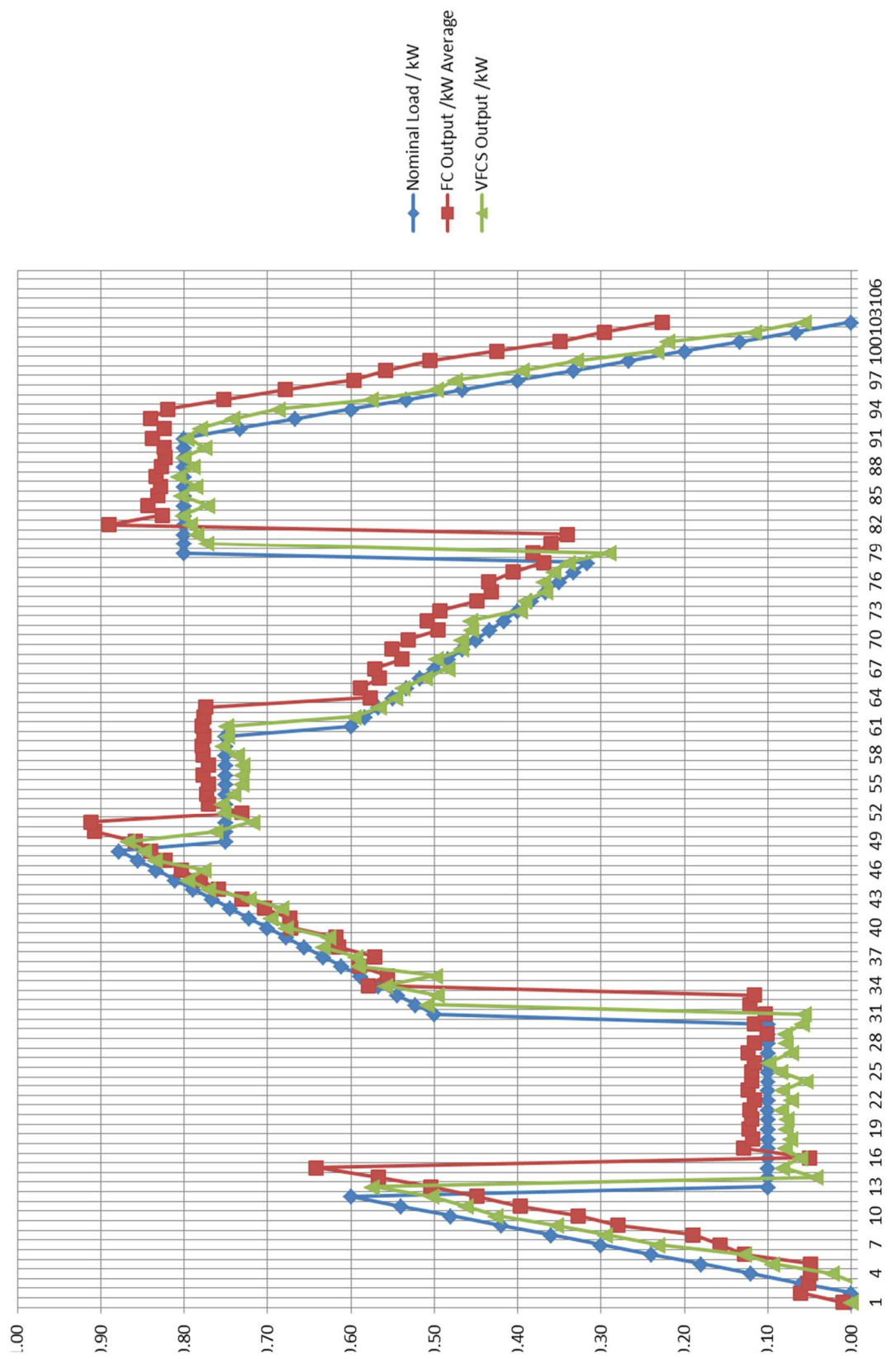
Profile 18 takes characteristics from all the previous load profiles and most closes represents the demands of a fuel cell in a vehicle.



Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.00	0.009	0.009	0.009	0.009	0.000
0.00	0.061	0.061	0.061	0.061	-0.006
0.06	0.051	0.051	0.050	0.051	-0.006
0.12	0.048	0.049	0.048	0.049	0.023
0.18	0.048	0.049	0.048	0.048	0.094
0.24	0.128	0.129	0.128	0.128	0.128
0.30	0.157	0.159	0.157	0.158	0.232
0.36	0.189	0.191	0.189	0.189	0.294
0.42	0.279	0.281	0.278	0.280	0.354
0.48	0.327	0.330	0.326	0.328	0.426
0.54	0.396	0.400	0.396	0.397	0.461
0.60	0.448	0.452	0.447	0.449	0.504
0.10	0.503	0.508	0.502	0.504	0.575
0.10	0.565	0.571	0.565	0.567	0.043
0.10	0.640	0.646	0.639	0.642	0.082
0.10	0.050	0.050	0.050	0.050	0.061
0.10	0.128	0.130	0.128	0.129	0.079
0.10	0.118	0.119	0.118	0.118	0.073
0.10	0.122	0.123	0.122	0.122	0.078
0.10	0.119	0.120	0.119	0.119	0.077
0.10	0.121	0.123	0.121	0.122	0.083
0.10	0.116	0.117	0.115	0.116	0.072
0.10	0.123	0.124	0.123	0.123	0.082
0.10	0.119	0.120	0.119	0.119	0.054
0.10	0.119	0.120	0.119	0.119	0.084
0.10	0.116	0.117	0.116	0.116	0.098
0.10	0.124	0.125	0.124	0.124	0.071
0.10	0.116	0.117	0.116	0.117	0.078
0.10	0.100	0.101	0.100	0.100	0.079
0.10	0.116	0.117	0.116	0.116	0.059
0.50	0.103	0.104	0.103	0.103	0.056
0.52	0.121	0.122	0.121	0.121	0.509
0.54	0.116	0.117	0.116	0.116	0.496
0.57	0.578	0.583	0.577	0.579	0.559
0.59	0.555	0.560	0.554	0.556	0.499
0.61	0.588	0.594	0.587	0.590	0.591

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.63	0.570	0.576	0.569	0.572	0.595
0.66	0.612	0.619	0.612	0.614	0.633
0.68	0.616	0.623	0.616	0.618	0.627
0.70	0.670	0.677	0.669	0.672	0.677
0.72	0.671	0.678	0.670	0.673	0.696
0.74	0.702	0.709	0.701	0.704	0.683
0.77	0.728	0.736	0.728	0.731	0.722
0.79	0.757	0.764	0.756	0.759	0.771
0.81	0.778	0.786	0.778	0.781	0.795
0.83	0.801	0.809	0.800	0.804	0.776
0.86	0.821	0.829	0.820	0.823	0.834
0.88	0.838	0.847	0.837	0.841	0.848
0.75	0.856	0.864	0.855	0.858	0.867
0.75	0.904	0.913	0.903	0.907	0.762
0.75	0.909	0.918	0.908	0.912	0.718
0.75	0.729	0.736	0.728	0.731	0.753
0.75	0.769	0.777	0.768	0.771	0.754
0.75	0.771	0.779	0.770	0.773	0.740
0.75	0.768	0.776	0.768	0.771	0.731
0.75	0.775	0.783	0.774	0.777	0.731
0.75	0.768	0.776	0.767	0.770	0.730
0.75	0.775	0.783	0.774	0.777	0.737
0.75	0.776	0.783	0.775	0.778	0.753
0.75	0.774	0.782	0.773	0.777	0.748
0.60	0.777	0.784	0.776	0.779	0.750
0.58	0.774	0.782	0.773	0.777	0.596
0.57	0.771	0.779	0.771	0.774	0.566
0.55	0.575	0.580	0.574	0.576	0.546
0.53	0.587	0.593	0.586	0.588	0.537
0.52	0.564	0.569	0.563	0.566	0.511
0.50	0.570	0.576	0.569	0.572	0.484
0.48	0.537	0.542	0.536	0.538	0.497
0.47	0.549	0.555	0.549	0.551	0.467
0.45	0.530	0.535	0.529	0.532	0.467
0.43	0.494	0.499	0.493	0.495	0.455
0.42	0.507	0.512	0.507	0.509	0.456
0.40	0.491	0.496	0.491	0.493	0.397
0.38	0.448	0.452	0.447	0.449	0.392
0.37	0.430	0.434	0.430	0.431	0.366
0.35	0.433	0.438	0.433	0.434	0.368
0.33	0.405	0.409	0.404	0.406	0.356
0.32	0.367	0.371	0.367	0.368	0.340
0.80	0.380	0.384	0.380	0.381	0.291
0.80	0.359	0.363	0.359	0.360	0.773
0.80	0.340	0.343	0.339	0.341	0.785
0.80	0.888	0.897	0.887	0.890	0.792
0.80	0.824	0.832	0.823	0.827	0.802
0.80	0.840	0.849	0.840	0.843	0.772
0.80	0.829	0.837	0.828	0.831	0.804
0.80	0.826	0.834	0.825	0.829	0.786
0.80	0.831	0.839	0.830	0.833	0.806
0.80	0.825	0.833	0.824	0.827	0.789
0.80	0.820	0.828	0.819	0.823	0.800
0.80	0.822	0.830	0.821	0.824	0.775
0.80	0.836	0.844	0.835	0.839	0.796
0.73	0.821	0.830	0.821	0.824	0.780

Nominal Load / kW	FC Output /kW Run 1	FC Output /kW Run 2	FC Output /kW Run 3	FC Output /kW Average	VFCS Output /kW
0.67	0.837	0.846	0.837	0.840	0.741
0.60	0.817	0.826	0.817	0.820	0.687
0.53	0.750	0.758	0.749	0.752	0.576
0.47	0.677	0.684	0.676	0.679	0.498
0.40	0.595	0.601	0.594	0.597	0.475
0.33	0.557	0.563	0.556	0.559	0.395
0.27	0.504	0.509	0.503	0.505	0.329
0.20	0.423	0.428	0.423	0.425	0.233
0.13	0.348	0.352	0.348	0.349	0.220
0.07	0.295	0.298	0.294	0.296	0.116



Chapter 14. References

- [1] Z. Lemes and N. Nicoloso, "Modelling Assisted Testing and Quality Control of Fuel Cells," presented at the 12th International Research/Expert Conference, TMT 2008 Istanbul Turkey, 2008.
- [2] J. Larminie and A. Dicks, *Fuel cell systems explained*, 2nd ed. ed. Chichester: Wiley, 2003.
- [3] J. H. Hirschenhofer, *Fuel cell handbook*, 4th ed. ed. Orinda, Calif.: B/T Books, 2000.
- [4] G. J. K. Acres, "Recent advances in fuel cell technology and its applications," *Journal of Power Sources*, vol. 100, pp. 60-66, 2001.
- [5] X. Li, *Principles of fuel cells*. New York ; London: Taylor & Francis, 2006.
- [6] F. Ommi, G. Pourabedin, and K. Nekofa, "Evaluation of Model and Performance of Fuel Cell Hybrid Electric Vehicle in Different Drive Cycles," *International Journal of Applied Science, Engineering and Technology*, vol. 5, pp. 246-252, 2009.
- [7] M. C. Pera, D. Hissel, and J. M. Kauffmann, "Fuel Cell Systems for Electrical Vehicles," presented at the IEE VTC, 2002.
- [8] J. T. Pukrushpan, A. G. Stefanopoulou, and H. Peng, *Control of fuel cell power systems : principles, modeling, analysis and feedback design*. London: Springer, 2004.
- [9] U. Stimming, L. Carette, and K. A. Friedrich, "Fuel cells: Principles, types, fuels and applications," *ChemPhysChem*, vol. 1, pp. 162-193, 2002.
- [10] L. Gauchia and J. Sanz, "Hardware-in-loop Simulation Platform for Energy Systems in Hybrid Electric Vehicles," *2008 IEEE International Symposium on Industrial Electronics, Vols 1-5*, pp. 1196-1201, 2008.
- [11] C. Rayment and S. Sherwin, "Introduction to Fuel Cell Technology," Department of Aerospace and Mechanical Engineering, University of Notre Dame, IN, USA, 2003.
- [12] F. Barbir, *PEM fuel cells : theory and practice*. Amsterdam ; London: Elsevier Academic, 2005.
- [13] S. Gunter and K. Kordesch, *Fuel Cells and their Application*. Weinheim: VCH, 1996.
- [14] E. Services, *Fuel cell handbook*, 5th ed. / prepared by EG&G Services, Parsons Inc., Science Applications International Corporation for U.S. Department of Energy, National Energy Technology Laboratory. ed. Orinda, Calif.: B/T Books, 2000.
- [15] M. H. Nehrir and C. Wang, *Modeling and control of fuel cells : distributed generation applications*. Hoboken, N.J.: Wiley, 2009.
- [16] S. Variginda and M. Kamat, "Control of stationary and transportation fuel cell systems: Progress and opportunities," *Computers and Chemical Engineering*, vol. 30, pp. 1735-1748, 2006.
- [17] R. M. Burer, "Multi-criteria optimization of a district cogeneration plant integrating a solid oxide fuel cell-gas turbine combined cycle, heat pumps and chillers," *Energy*, vol. 28, pp. 497-518, 2002.
- [18] R. P. O'Hayre, *Fuel cell fundamentals*, 2nd ed. ed. Hoboken, N.J.: John Wiley & Sons, 2009.
- [19] G. Paganelli, Y. Guezennec, G. Rizzoni, and G. Moran, "Proton exchange membrane fuel cell system model for automotive vehicle simulation and control," *Journal of Energy Resources Technology-Transaction of the ASME*, vol. 124, pp. 20-27, 2002.

- [20] C. Graf, K. A. Friedrich, A. Vath, and N. Nicoloso, "Dynamic Load and Temperature Behaviour of a PEFC-Hybrid-System," *Journal of Fuel Cell Science and Technology*, vol. 3, pp. 403-409, 2006.
- [21] G. Hinds, *Preparation and characterisation of PEM fuel cell electrocatalysts : a review*. Teddington: National Physical Laboratory, 2005.
- [22] F. Mitlitsky, B. Myers, and A. H. Weisberg, "Regenerative Fuel Cell Systems," *Energy & Fuels*, vol. 12, pp. 56-71, 1998.
- [23] S. J. Paddison, K. Promislow, and SpringerLink ebooks - Physics and Astronomy (2009). (2009). *Device and materials modeling in PEM fuel cells*. Available: <http://0-link.springer.com.library.newcastle.edu.au/openurl?genre=book&isbn=978-0-387-78690-2>
- [24] C.-J. Sjøstedt, D.-J. Chen, P. Prenninger, and I. Faye, "Virtual Component Testing for PEM Fuel Cell Systems: An Efficient, High Quality and Safe Approach for Supplier and OEM's," presented at the 3rd European PEFC Forum, Europe, 2009.
- [25] R. M.T. Outeiro, Chibante, A.S.Carvalho, A.T. deAlmeida, "A Parameter Optimized Model of a Proton Exchange Membrane Fuel Cell Including Temperature Effects," *Journal of Power Sources*, vol. 185, pp. 952-960, 2008.
- [26] Y. Shan and S.-Y. Choe, "Modeling and simulation of a PEM fuel cell stack considering temperature effects," *Journal of Power Sources*, vol. 158, pp. 274-286, 2005.
- [27] C. Thawornkuno and C. Panjapornpon, "Estimation of water content in PEM fuel cell," *Chiang Mai Journal of Science*, vol. 35, pp. 212-220, 2008.
- [28] I. Univeristy of California. (2013). *National Fuel Cell Research Center*.
- [29] Energy.gov. (2013). *Office of Energy Efficiency and Renewable Energy*.
- [30] J. Bingham, *The Hindenburg, 1937 : a huge airship destroyed by fire*. Oxford: Raintree, 2006.
- [31] f. foundation. (2010). *Hydrogen Safety - 5. Gasoline Vs. Hydrogen*.
- [32] G. F. McLean, T. Niet, S. Prince-Richard, and N. Djilali, "An Assessment of Alkaline Fuel Cell Technology," *International Journal of Hydrogen Energy*, vol. 27, pp. 507-526, 2002.
- [33] S. M. Haile, "Fuel Cell Materials and Components," *Acta Materialia*, vol. 51, pp. 5981-6000, 2003.
- [34] D. Brown, "Simulation and Optimization of a Fuel Cell Hybrid Vehicle," Master of Science, Mechanical Engineering, University of Delaware, ProQuest, 2008.
- [35] S. Gupta, S. Singh, L. Mathew, and S. S.L, "Comparative Study of DC to DC convertors via Simpowerelectronics Fuel Cell Stack," *IOSR Journal of Engineering (IOSRJEN)*, vol. 4, pp. 13-21, 2014.
- [36] S. Y. Choe, J.-W. Ahn, J.-G. Lee, and S.-H. Baek, "Dynamic Simulator for a PEM Fuel Cell System with a PWN DC/DC Converter," *IEEE Transactions on Energy Conversion*, vol. 23, pp. 669-681, 2008.
- [37] M. Uzunoglo, O. C. Onar, and M. S. Alam, "Modeling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications," *Journal of Renewable Energy*, vol. 34, pp. 509-520, 2009.
- [38] M. I. a. Rosli, "Water management in PEM fuel cell gass distributor plates," Thesis (Ph.D.), University of Leeds, 2011.

- [39] **G. Crawley.** (2007) **Solid Oxide Fuel Cells (SOFC). *FUEL CELL TODAY.***
- [40] F. C. Etc. (2013). *Fuel Cell FAQs / Molten Carbonate Fuel Cell (MCFC).*
- [41] J. T. Pukrushpan, "Modelling and Control of Fuel Cell Systems and Fuel Processors," Doctor of Philosophy, Mechanical Engineering, The University of Michigan, 2003.
- [42] A. Rowe and X. Li, "Mathematical modeling of proton exchange membrane fuel cells," *Journal of Power Sources*, vol. 102, pp. 82-96, 2001.
- [43] C. Dufour, T. Ishikawa, S. Abourida, and J. Belanger, "Modern Hardware-In-The-Loop Simulation Technology for Fuel Cell Hybrid Electric Vehicles," ed: IEEE, 2007.
- [44] S. Ibrir and D. Cheddie, "Model-based estimation of PEM fuel-cell systems," presented at the IEEE International Symposium on Intelligent Control, St Petersburg, Russia, 2009.
- [45] Z. H. Jiang, R. Leonard, R. Dougal, H. Figueroa, and A. Monti, "Processor-in-the-loop simulation, real-time hardware-in-the-loop testing, and hardware validation of a digitally-controlled, fuel-cell powered battery-charging station," *Pesc 04: 2004 IEEE 35th Annual Power Electronics Specialists Conference, Vols 1-6, Conference Proceedings*, pp. 2251-2257, 2004.
- [46] J.-H. Jung and S. Ahmed, "Dynamic Model of PEM Fuel Cell Using Real-time Simulation Techniques," *JPE 10-6-22*, pp. 739-748, 2010.
- [47] Z. Lemes, A. Vath, T. Hartkopf, and H. Mancher, "Dynamic fuel cell models and their application in hardware in the loop simulation," *Journal of Power Sources*, vol. 154, pp. 386-393, 2006.
- [48] H. Mancher and H. Manske, "Hardware-in-the-loop ready fuel cell test stands as a development platform Cost saving and efficiency improvement through use of test stand simulation," *Open-Loop and Closed-Loop Control of Vehicles and Engines - Autoreg 2004*, vol. 1828, pp. 715-719, 2004.
- [49] C. Martinez Baca Velasco. (2007). *Computational model of a PEM fuel cell.*
- [50] R. M. Moore, K. H. Hauer, G. Randolph, and M. Virji, "Fuel cell hardware-in-loop," *Journal of Power Sources*, vol. 162, pp. 302-308, 2006.
- [51] C. Panos, K. I. Kouramas, M. C. Georgiadis, N. Brandon, and E. N. Pistikopoulous, "Modelling and Explicit MPC of PEM Fuel Cell Systems," presented at the 20th European Symposium on Computer Aided Process Engineering - ESCAPE20, Europe, 2010.
- [52] G. Randolph and R. M. Moore, "Test system design for Hardware-in-Loop evaluation of PEM fuel cells and auxiliaries," *Journal of Power Sources*, vol. 158, pp. 392-396, 2006.
- [53] J. P. Iuscu and C. R. Ozansoy, "Title," unpublished].
- [54] J. Chen and B. Zhou, "Diagnosis of PEM fuel cell stack dynamic behaviors," *Journal of Power Sources*, vol. 177, pp. 83-95, 2007.
- [55] d. GmbH. (2006) Testing Fuel Cell Technology. *dSpace News*.
- [56] J. J. Baschuk and X. Li, "A comprehensive, consistent and systematic model of PEM fuel Cells," *Journal of Applied Energy*, vol. 86, pp. 181-193, 2009.
- [57] Z. Zhang, X. Huang, J. Jiang, and B. Wu, "An improved dynamic model considering effects of temperature and equivalent internal resistance for

- PEM fuel cell power modules," *Journal of Power Sources*, vol. 161, pp. 1062-1068, 2006.
- [58] W. H. Zhu, R. U. Payne, R. M. Nelms, and B. J. Tatarchuk, "Equivalent circuit elements for PSpice simulation of PEM stacks at pulse load," *Journal of Power Sources*, vol. 178, pp. 197-206, 2008.
- [59] T. E. Springer and S. Gottesfeld, "Polymer Electrolyte Fuel Cell Model," *The Electrochemical Society*, vol. 138, 1991.
- [60] H. Wang, X.-Z. Yuan, H. Li, and Ebook library. (2011). *PEM Fuel Cell Diagnostic Tools*. Available: <http://library.newcastle.edu.au/screens/EBL-instructions.html> Available: <http://0-newcastle.ebilib.com.library.newcastle.edu.au/patron/FullRecord.aspx?p=777173>
- [61] C. Spiegel, *Designing and building fuel cells*. New York: McGraw-Hill ; London : McGraw-Hill [distributor], 2007.
- [62] K. Haraldsson and K. Wipke, "Evaluating PEM and fuel cell system models," *Journal of Power Sources*, vol. 126, pp. 88-97, 2004.
- [63] F. Gao, B. Blunier, D. Bouquain, and A. El-Moudni. (2010) Emulateur de piles a combustible pour applications de Hardware in the Loop. *REE*.
- [64] D. F. Cheddie and N. D. H. Munroe, "Semi-analytical proton exchange membrane fuel cell modeling," *Journal of Power Sources*, vol. 183, pp. 164-173, 2008.
- [65] F. Gao, B. Blunier, and M. Abdellatif, *Proton Exchange Membrane Fuel Cells Modeling*. London, UK: ISTE Ltd, 2012.
- [66] K. Hard. (2005). *PEM fuel cell multi-phase system*.
- [67] A. Haddad, R. Bouyekhf, and A. El Moudni, "Dyanmic modelling and water management in proton exchange membrane fuel cell," *International Journal of Hydrogen Energy*, vol. 33, pp. 6239-6252, 2008.
- [68] S. Wang. (2006). *Advanced air fuel ratio control of automotive si engines* [1 v. ; 31 cm.].
- [69] J. C. Amphlett, R. F. Mann, B. A. Peppley, and P. R. Roberge, "Performance modeling of the Ballard Mark IV solid polymer electrolyte fuel cell," *Mechanistic and Model Development Electrochemical Sociey*, vol. 142, p. 1, 1995.
- [70] C. Dufour, J. Belanger, T. Ishikawa, and K. Uemura, "Advances in Real-Time Simulation of Fuel Cell Hybrid Electric Vehicles," presented at the 21st Electric Vehicle Symposium (EVS-21), Monte Carlo, Monaco, 2005.
- [71] C. Dufour and J. Belanger, "Real-Time Simulation of Fuel Cell Hybrid Electric Vehicles," presented at the International Symposium on Power Electronics, Electric Drives, Automation and Motion, 2006.
- [72] B. He, M. G. Yang, J. Q. Li, and L. G. Lu, "Real-time vehicle system controller design for a hybrid fuel cell bus," *Proceedings of the ASME Power Conference 2005, Pts A and B*, pp. 1011-1019, 2005.
- [73] M. Salem, T. Das, and X. Chen, "Real time simulation for speed control of switched reluctance motor drive powered by a fuel cell system," *Proceedings of the ASME Power Conference 2005, Pts A and B*, pp. 923-928, 2005.
- [74] J. Belanger, P. Venne, and J.-N. Paquin, "The What, Where and Why of Real-Time Simulation," presented at the IEEE, 2012.
- [75] Y. H. Hung, P. H. Lin, C. H. Wu, and C. W. Hong, "Real-time dynamic modeling of hydrogen PEMFCs," *Journal of The Franklin Institute*, vol. 345, pp. 182-203, 2008.
- [76] L. Fang and L. Yang Ru, "Title," unpublished].

- [77] M. Usman Iftikhar, D. Riu, F. Druart, R. S., Y. Bultel, and N. Retiere, "Dynamic modeling of proton exchange membrane fuel cell using non-integer derivatives," *Journal of Power Sources*, vol. 160, pp. 1170-1182, 2006.
- [78] M. Meiler, O. Schmid, M. Schudy, and E. P. Hofer, "Dynamic fuel cell stack model for real-time simulation based on system identification," *Journal of Power Sources*, vol. 176, pp. 523-528, 2007.
- [79] d. GmbH. (2010) Full Power - Green Success. *dSpace Magazine*.
- [80] C. Spiegel, *PEM fuel cell modeling and simulation using Matlab*. London: Academic, 2008.
- [81] R. Taylor, V. Pickert, and M. Armstrong, "Evaluating the Suitability of Available Proton Exchange Membrane (PEM) Fuel Cell Models for use in a Virtual Fuel Cell System," presented at the Newcastle University EECE Conference, 2011.
- [82] P. Corbo, F. Migliardini, and O. Veneri, "Dynamic behaviour of hydrogen fuel cells for automotive application," *Renewable Energy*, pp. 1-7, 2009.
- [83] M. Amrhein and P. T. Krein, "Dynamic Simulation for Analysis of Hybrid Electric Vehicle System and Subsystem Interactions Including Power Electronics," *IEEE Transactions on Vehicular Technology*, vol. 54, pp. 825-836, 2005.
- [84] M. De Francesco and E. Arato, "Start-up Analysis for Automotive PEM Fuel Cell Systems," *Journal of Power Sources*, vol. 108, pp. 41-52, 2002.
- [85] A. Emadi, *Handbook of automotive power electronics and motor drives*. Boca Raton, Fla. ; London: Taylor & Francis/CRC Press, 2005.
- [86] P. Pei, W. Yang, and P. Li, "Numerical prediction on an automotive fuel cell driving system," *International Journal of Hydrogen Energy*, vol. 31, pp. 361-369, 2005.
- [87] W. Jiang, J. Kahn, and R. A. Dougal, "Dynamic centrifugal compressor model for system simulation," *Journal of Power Sources*, vol. 158, pp. 1333-1343, 2006.
- [88] R. T. Meyer and B. Yao, "Control of a PEM Fuel Cell Cooling System," presented at the ASME International Mechanical Engineering Congress and Exposition, Chicago, Illinois, USA, 2006.
- [89] P. Rodatz, C. Onder, and L. Guzzella, "Air Supply System of a PEMFC Stack Dynamic Model," ed. Zurich Switzerland: Wiley-VCH, 2004, pp. 126-132.
- [90] B. Sun, W. Turner, M. Parten, and T. Maxwell, "Instrumentation of a PEM Fuel Cell Vehicle," Electrical and Computer Engineering, Texas Tech University, 2001.
- [91] D. Thirumalai and R. E. White, "Steady-state operation of a compressor for a proton exchange membrane fuel cell system," *Journal of Applied Electrochemistry*, vol. 30, pp. 551-559, 2000.
- [92] P. Thounthong, B. Davat, S. Rael, and P. Sethakul. (2009) Fuel Starvation: Analysis of a PEM fuel-cell system. *IEEE Industry Applications Magazine*. 52-59.
- [93] Q. Yang, A. Aitouche, and B. O. Bouamama, "Structural Analysis for Air Supply System of Fuel Cell," presented at the International Renewable Energy Congress, Sousse, Tunisia, 2009.
- [94] G. W. Kulp, "A Comparison of Two Air Compressors for PEM Fuel Cell Systems," Master of Science, Mechanical Engineering, Virginia Polytechnic Institute and State University, 2001.

- [95] C. Xiaokai, Z. Hong, L. Yi, and L. Shaojia, "Simulation-Based Analysis and Robust Design of Fuel Cell Electric Vehicle Cooling System," presented at the IEEE Vehicle Power and Propulsion Conference, Harbin, China, 2008.
- [96] R. Timovan and S. Giurgea, "Surrogate modelling of compressor characteristics for fuel cell applications," *Journal of Applied Energy*, vol. 85, pp. 394-403, 2008.
- [97] J. M. Cunningham, M. A. Hoffman, R. M. Moore, and D. J. Friedman, "Requirements for a flexible and realistic air supply model for incorporation into a fuel cell vehicle (FCV) system simulation," presented at the SAE Paper, 1999.
- [98] J. B. Heywood, *Internal combustion engine fundamentals*: McGraw-Hill, 1988.
- [99] H. Wang, H. Li, X.-Z. Yuan, and Ebook library. (2011). *PEM Fuel Cell Failure Mode Analysis*. Available: <http://library.newcastle.edu.au/screens/EBL-instructions.html> Available: <http://0-newcastle.ebilib.com.library.newcastle.edu.au/patron/FullRecord.aspx?p=777174>
- [100] A. Gebregergis and P. Pillay, "Implementation of Fuel Cell Emulation on DSP and dSpace Controllers in the Design of Power Electronic Converters," *IEEE Transactions on Industry Applications*, vol. 46, pp. 285-294, 2010.
- [101] Z. Lemes, M. Worbelaue, I. Nicoloso, and C. Henschel, "Online Diagnostics for Fuel Cells using Hardware-in-the-Loop capable Test Benches," *MAGNUM Fuel Cell your partner in technology*.
- [102] H. H. Ottesen, "Dynamic Performance of the Nexa Fuel Cell Power Module," ed. Rochester, Minnesota: Rochester Public Utilities, 2004.
- [103] F. Gao, B. Blunier, A. Miraoui, and A. El-Moudni, "Cell layer level generalized dynamic modeling of a PEMFC stack using VHDL-AMS language," *International Journal of Hydrogen Energy*, vol. 34, pp. 5498-5521, 2009.
- [104] A. Yilanci, H. K. Ozturk, O. Atalay, and I. Dincer, "Title," unpublished|.